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IMAGE SCANNER TECHNOLOGY STUDY

Final Technical Report

John Montuori

PERKIN-ELMER

Optical Technology Division

March 1978

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This study evaluates available image scanning technologies as they relate to the requirements for providing inputs to digital mapping systems.

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Abstract:

This study evaluates available image scanning technologies as they relate to the requirements for providing inputs to digital mapping systems.

PREFACE

This survey of image scanning technology was performed at the request of the Engineering Topographic Laboratories (ETL). The personnel at ETL having cognizance over the effort include Mr. M. Crombie and Mr. L. Gambino.

The writer was assisted by R. Arguello, L. Beiser, L. Cassidy, R. Labinger and others.

The data presented in the report was compiled by researching various technical journals, by extracting from brochures in our files and by using the experience gained from in-house programs.

SUMMARY

This study was undertaken to evaluate currently available image scanning technologies as they relate to the requirements for providing inputs to digital mapping systems. Functional and performance requirements for a scanning/digitizing system are discussed and various scanner technologies -- electronic, electro-optical, and solid-state -- are described and compared with respect to the requirements.

The critical requirements imposed on an image scanner for digital mapping applications are resolution (in total number of elements per viewing area), uniformity of performance over that area, geometric accuracy, and speed. Resolution, uniformity, and accuracy appear to be beyond the capability of flexibily-scanned systems, both electron-beam or laser-beam-addressed.

Even the highest-performance electron-beam systems are not capable of covering the full format with the requisite number of resolution elements at sufficiently high contrast and detectability to allow adequate dynamic range and scan linearity. The montaging of strips or areas of sub-rasters to allow the use of such systems is extremely unattractive because of the critical edge-matching requirements to achieve continuity with accuracy.

The various mapping applications are best accomplished with different operating modes. Some require scanning a full format (230 x 230 mm maximum area) whereas a smaller "window" scanning mode suffices for others. In some cases, an interactive capability would be beneficial, in others, batch processing is better. Systems adaptable to all these requirements include drum-type laser scanners, rotating-mirror laser scanners, and solid-state scanners comprised of a series of optically butted linear arrays. In all cases, careful design and implementation are essential.

The rotating drum and mirror approaches are inefficient in the window mode because of their duty cycle, whereas the solid-state approach is equally efficient in both the full format and window modes.

If different scanners are planned for each mode, then oscillating mirror technology, in conjunction with precision positioning stages, can be adapted to satisfy a "window only mode." Some of the electronic scanners can also be adapted to the "window only mode" if geometric and photometric accuracy requirements are relaxed.

It should also be noted that most of the scanning technologies discussed in this report have a relatively long history (15-30 years). The embodiments of scanner systems using these technologies have thus benefitted from significant developments over these relatively long periods and can be taken to represent near maximum or optimum refinement. One technology, however, is relatively new and has not benefitted from many years of refinement. This technology, solid-state imaging arrays, will very likely see significant improvement in the coming years. Certainly, the relative infancy of this solid-state array technology and the rapid rate at which refinements in terms of number of elements per array, element size and spacing, and noise characteristics are being introduced strongly suggests that their capabilities and associated implementation simplicity will far surpass other alternatives for most scanning applications in the very near future.

The operating environment intended for the scanner, i.e., production or research and development, also significantly influences the requirements imposed on it. Consequently, it is concluded that the application scenario and intended environment must be known and resulting requirements carefully evaluated and ranked before the most appropriate technology can be selected and a system design recommended.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF TABLES

SECTION 1

INTRODUCTION

This study was undertaken to evaluate currently available image scanning technologies as they relate to the requirements for providing inputs to digital mapping systems.

The steadily increasing data requirements imposed on the mapping community are forcing the development of automatic systems for map production. Emphasis is on both speed and accuracy, and especially on the reduction of the labor-intensive parts of the map-making process. Since much of the map data is derived from aerial photographs, a system to rapidly convert these sources into the proper digital data form is becoming necessary.

The magnetic storage required for a typical medium to high resolution photographic image in digital form is large (from 10^9 to 10^{10} bits, or more). Therefore, it is not now a practical medium for the archival storage of many images. A viable alternative to digitizing and storing entire frames of imagery is to scan, digitize, and temporarily store the required sections of an image when and as required for digital processing. Using this alternative eliminates the need for a large permanent magnetic storage since the image stored in photographic form serves as a massive read-only memory.

In order to convert pictorial data to digital form, an analog signal related to the transmissive variations in an image on film must be generated. The analog signal is then sampled and quantized into discrete digital numbers for use as computer input. There are several alternative approaches to the implementation of this conversion process, including microdensitometers, laser scanners, flying spot scanners, solid-state array scanners, and vidicon scanners. Each has its own capabilities and limitations, which should be

considered with regard to the task that must be performed. The trade-offs among them include speed, resolution, accuracy (both geometric and radiometric) and cost. Optimization of the trade-offs depends on the application, and requires the prospective user determine the relative importance of these parameters for his specific application. For example, mensuration precision may be required for precise location of details in a scene, but for many applications, exact positional information may be unimportant. Speed requirements vary greatly; a production facility may require the digitization of large amounts of data in a day, while in a research and development application speed may not be considered important. Similarly, micro-densitometers might be suited to off-line bulk conversion of film imagery to digital form with high accuracy and high resolution, but they are definitely too slow to support on-line utilization during interactive processing. Vidicon scanners, at the other end of the spectrum, are fast enough for interactive use, but are subject to large distortions, which must be compensated for by appropriate calibration. Between these two are other alternatives representing various levels of conversion rates, metric performance, and potential constraints on production process design.

This report derives a set of application-oriented specifications for scanning/digitizing systems and indicates how the various available scanning technologies meet these requirements.

Recommendation of a specific design approach for a scanner was not an objective of this study.

SECTION 2

REQUIREMENTS

2.1 GENERAL

Practical systems design involves trade-offs between various realistic requirements and the technically feasible features of an ideal image digitization system. Realistic requirements are application-dependent. Consequently, details of the specific applications intended for a scanner, including the characteristics of the inputs and output, should be carefully considered in specifying its performance. Since no specific application-oriented specifications for an image scanner were available at the beginning of this study, typical mapping-related applications for digitized image data were considered with the intention of deriving performance requirements to serve as a basis of comparison for candidate scanner technologies. The purpose of this section of the report is to identify the important functions that should be implemented in an image scanner used primarily in support of digital mapping operations, and, where possible, to establish performance requirements for them.

2.2 BASIC FUNCTIONAL REQUIREMENTS

There are three basic functions associated with any image scanner whose purpose is to provide input to a digital processing system. They are shown in Figure 2-1 and listed below:

- Digitize image areas, either selected areas within an input format or the entire format area.
- Provide coordinate information that relates each pixel to all others, with regard to location in pixel space, and also relates pixel space to input image space.

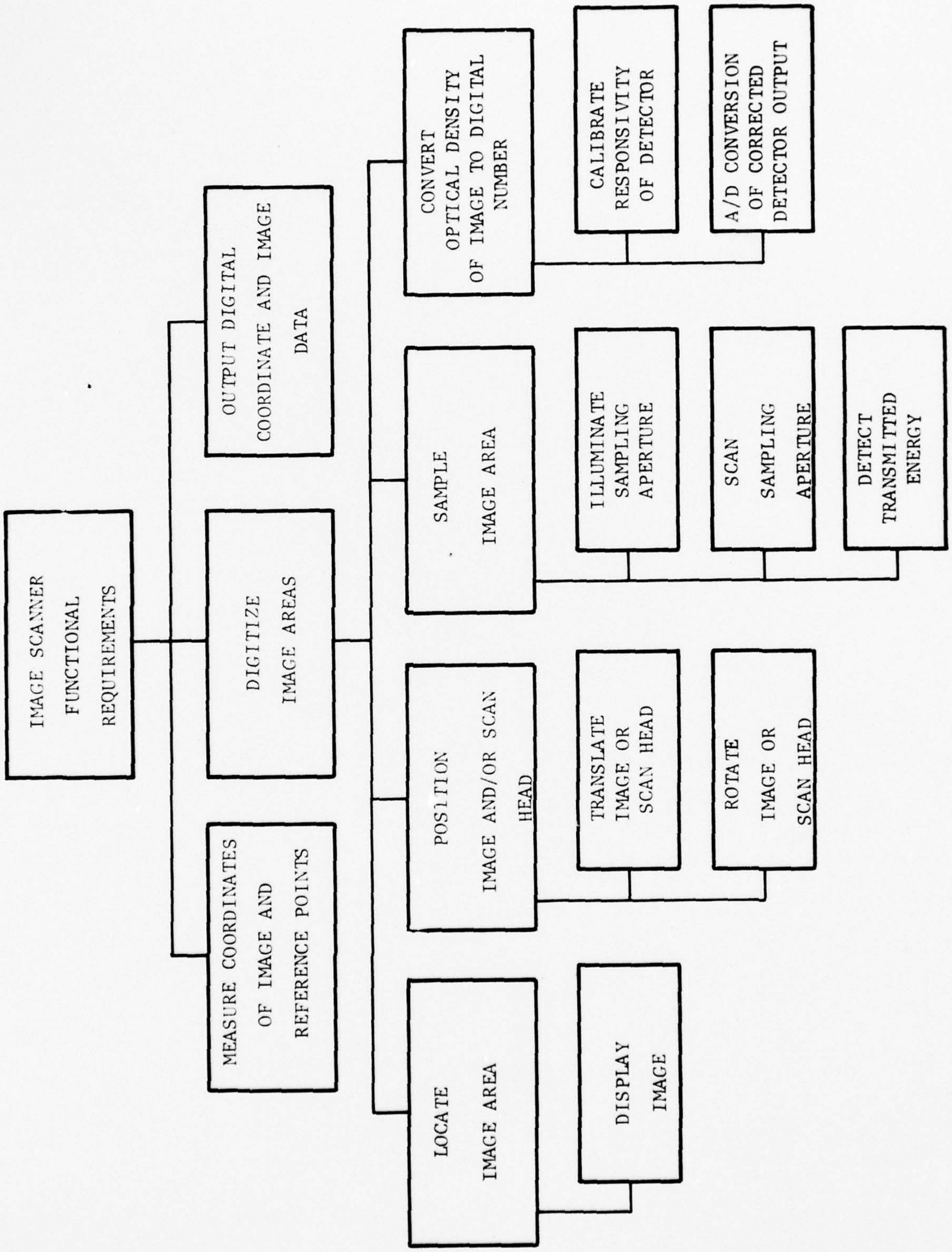

Figure 2-1. Basic Functional Requirements of An Image Digitizer

- Output digital image and coordinate data directly to a using system or to some intermediate storage medium.

Figure 2-1 also shows a set of secondary functions that must be implemented in order to digitize image areas. The implementation and performance requirements associated with the functions, however, depend upon the specific uses intended for the digital output of the device as well as the manner in which the scanner itself is to be used, i.e., in a production or research and development (R&D) environment, and whether it will be used on-line, interactively, or off-line.

Speed, degree of automation, flexibility and cost are features that vary in importance with the operational environment intended for the scanner; whereas resolution, geometric and radiometric accuracies, and format accommodation are more application-dependent.

The on-line versus off-line versus interactive considerations mostly influence the *implementation* requirements associated with the coordinate measurement and the output interface.

2.2.1 Production Versus R&D Environment

A production environment generally places a higher priority on throughput rates, low daily operating costs and, consequently, automation, than it does on flexibility and initial cost. Typically, universal flexibility is not required for a production environment because the scanner should be designed to accommodate the functions required to perform specific map production operations in a manner that optimizes throughput and minimizes operating costs.

Flexibility, however, is an important feature in an R&D environment because different capabilities are required to support a variety of experiments that are designed to explore new approaches to many problems and to demonstrate their feasibility. Automation and speed, on the other hand, have a lower priority because it is usually very difficult to justify the higher initial costs associated with desireable but unnecessary features.

2.2.2 On-Line Versus Off-Line Versus Interactive Operation

Three alternative output interfaces are shown in Figure 2-2. The first would be used in a batch type of operation where the images to be processed are digitized off-line with regard to the main data processing computer and stored temporarily on disks that can be moved to the processing center as required.

The second alternative shown differs from the first in that the output interface design puts the scanner on-line with the main data-processing computer via a peripheral control computer and disk storage. The control computer serves as a traffic director and data formatter, while the disc temporarily stores the data until called for by the data-processing unit.

The third alternative shown in the figure accommodates an interactive mode of operation. The significant difference between it and the previous alternative is that scanner control and operation, except for the loading of input film, are accomplished at a station that is physically removed from the scanner itself. This adds complexity and cost to the scanner. Furthermore, a quick response capability, with respect to accessing different areas of an input format, is required to make the interactive alternative a viable one.

The data rate requirements imposed on a scanner by the three types of interface shown in Figure 2-2 are essentially the same if the system designer elects to use the limitations of the storage device to set requirements for the scanner. Typical disk systems such as the standard CDC-844 used at the USAETL's Digital Image Analysis Laboratory (DIAL) can accommodate transfer rates up to 6×10^6 bits/sec, ignoring software overhead.[1] Assuming density level encoding at 8 bits per pixel sets an upper limit on the data rate at approximately 0.75×10^6 pixels/sec for these types of installation. The

[1] References are given in Section 6.

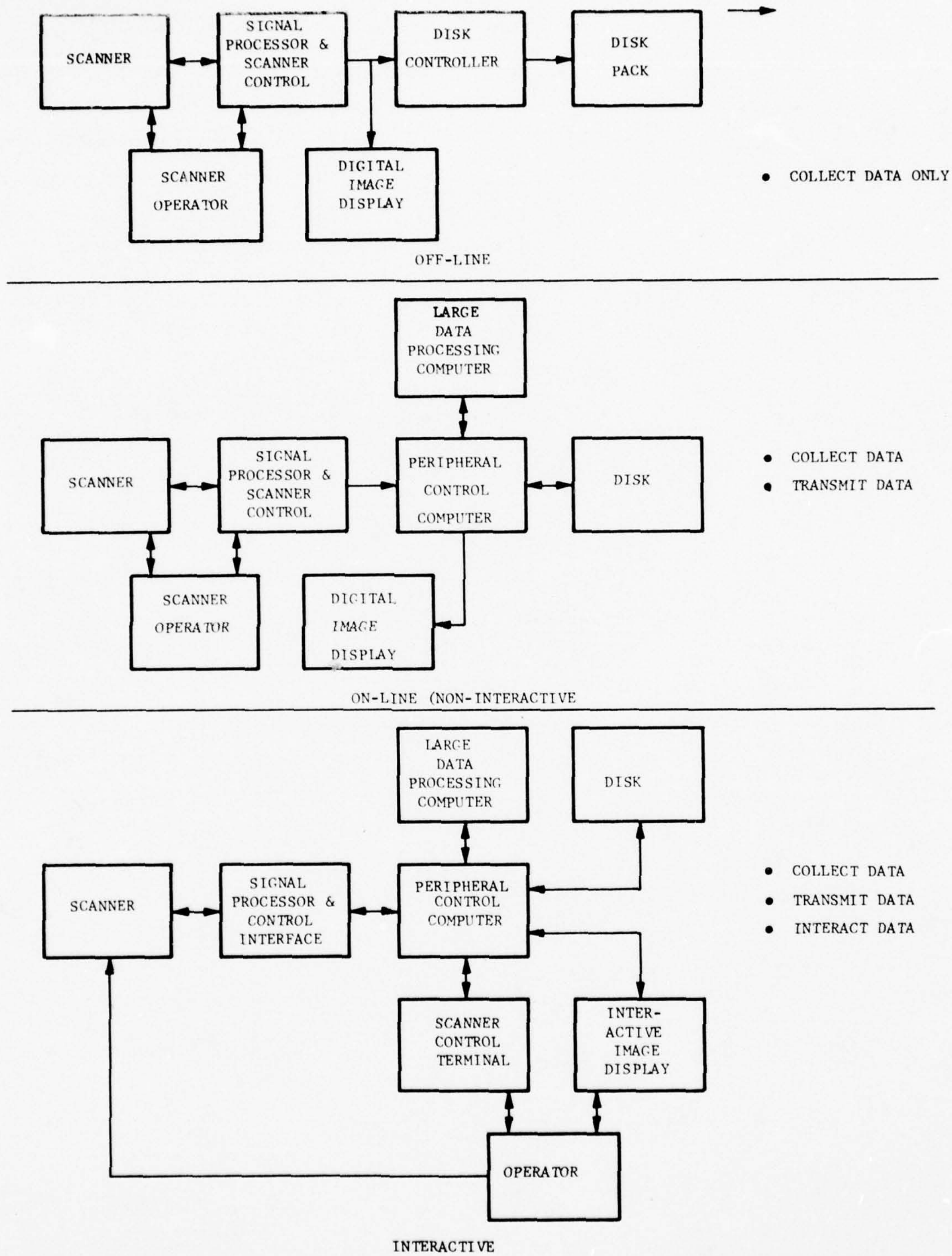

Figure 2-2. Alternative Operating Modes and Interfaces

DIAL system is currently being expanded and the new configuration is expected to accommodate up to 1.25×10^6 pixels/sec. However, development of a special interface device between the Extended Core Storage (ECS) of the DIAL system and a non-standard device such as the STARAN parallel processor would provide a potential for a very high data transfer bandwidth into the parallel input and output ports of the STARAN. These data rates would accommodate transfers on the order of 1.85×10^7 pixels/sec with one bank of ECS and twice that if a second bank were added to the system.[1] This capability is representative of a fourth alternative not shown in Figure 2-2, that of interfacing directly with the large data-processing facility via special interfacing modules.

The necessity or advisability of operating on-line or interactively, opposed to off-line, is also very dependent on the specific application intended for the digitized data. Consequently, some relevant aspects of typical applications will now be considered before proceeding with the derivation of requirements.

2.2.3 Typical Applications for Digitized Image Data in Map Production Processes

There are three major tasks associated with the mapping process for which automatic digital data-processing techniques are being developed to speed up the processes and relieve some of the labor-intensive aspects of the tasks. These include:

- Stereo Photogrammetry - including contouring, determination of the elevation of discrete points, profiling, and the accurate determination of ground coordinates for discrete points from pairs of stereo images.

- Feature Extraction - involving the generation and maintenance of feature signature data bases via the analysis of texture and tonal information extracted from black and white imagery, and the subsequent automatic feature classification via the analysis of texture and tonal information on a variety of input images and comparison with feature signature data base.
- Feature Positioning - including image rectification and orthorectification.

2.2.3.1 Stereo Photogrammetry

There are two major functional requirements associated with all digital stereo photogrammetric tasks: the image space coordinates of corresponding image points must be determined so that the geometry at the time of image acquisition can be recovered using analytical intersection techniques; and, parallax information must be extracted from these coordinates to derive the elevation data.

Parallax is usually determined by comparing image space coordinates of corresponding points. The coordinates themselves are determined by the following series of operations.

- Digital correlation algorithms are used to match and identify corresponding image points in the stereo images.
- Scanner space coordinates of the matched points are determined from their locations in the bit stream.
- Scanner space is mapped into image space to derive the image coordinates of corresponding points.

In order for a match process to be efficiently developed on a digital computer, the search for corresponding points should be confined, as nearly as possible, along the direction of major parallax.[1] In photogrammetry this

observation translates into searching along the appropriate epipolar line.* If there is a large angular difference between a scan line and the local epipolar lines, then the algorithm that exploits epipolar geometry will require more computer storage and processing than if scan lines were nearly parallel to epipolar lines.

For those image acquisition situations where epipolar lines on each exposure are parallel to each other, but not parallel with the projected base line, the capability of rotating the image in the scanner such that scan lines are parallel to the epipolar lines would be a very desireable feature. However, some image acquisition geometries, for example, convergent photography, produce images having diverging rather than parallel epipolar lines within a single frame of imagery. For these situations a fixed rotation would not necessarily alleviate the computer storage problem significantly over large portions of a frame, whereas a continuously variable scanner rotation under computer control could maintain the desired degree of parallelism during the scanning period. A trade-off analysis weighing the added complexity of a computer-controlled, continuously variable rotation capability against the disadvantages of additional computer storage would have to be made to clearly establish the need for the more complex approach. Such a trade-off will be influenced by the characteristics of the specific classes of input images to be accommodated by the system. In addition to cost, a continuously variable rotation capability will have a significant impact on achieving required system accuracy from a coordinate measurement point of view.

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*An epipolar line pair is generated by the intersection of the epipolar plane and the two focal surfaces. An epipolar plane is any member of the family of planes defined by the straight line connecting the two exposure positions. Consequently, the corresponding images of any point in object space that lies on the section defined by the intersection of an epipolar plane and the surface of the earth will appear on corresponding epipolar lines.

The image matching process also requires a two-dimensional array of points from each image for correlation. The number of pixels required and the sampling interval required for each match are influenced by the degree to which the process is geometrically controlled (how well exterior and interior orientation are known), the required output accuracy, and operational economics. Furthermore, sampling spot size should be variable to accommodate different image scales, resolutions, and levels of information content.

The coordinate transformations required to relate individual pixels in the digital bit stream to positions in original image space impose some metric requirements on the scanner. The mapping of pixels into coordinates in scanner space is accomplished by applying the sampling interval factor to the pixel and line counts. Consequently, the linearity of the scanning process is an important characteristic, and it should be calibrated and repeatible.

The transformation from scanner space into image space is usually accomplished by measuring the coordinates in scanner space of reseau and fiducial points appearing on the film. The coordinates are then compared with calibration data to determine offsets and rotation, or a warping function, with respect to image space. This function is then applied to all scanner coordinates to accomplish the transformation.

This need to relate pixel locations in a bit stream to coordinates in image space imposes a mensuration requirement on scanner implementation. If full formats are being scanned, the requirement would be to measure fiducials which are normally located along the edges of the format, or to measure reseau points if a calibrated reseau is part of the image being scanned. If the scanning is limited to specific window areas throughout the format and a precalibrated reseau is not included with the image, it would still be necessary to measure fiducials along the edges of the format. Since 9 x 9 inch formats are common inputs to mapping systems, the measuring system should be

capable of coordinate readout over approximately 230 mm along two orthogonal axes. The accuracy of measurement of these distances should be on the order of 3 to 5 micrometers to be commensurate with the capabilities of currently used measuring instruments. A precision of 1 micrometer is desireable.

Three alternative operating modes, with regard to coordinate measurement, are shown in Figure 2-3. Measurements can be made by an operator working directly at the scanning station, wherein the capability to align or register a reference reticle with selected image points must be provided. In this case the operator would simultaneously view the image and the reticle while translating the image and/or optics to bring the selected image point into coincidence with the reticle.

Implementation to satisfy this mode is less complex than the others. Direct viewing through optics would be satisfactory, and the required translations can be accomplished either manually or electrically with appropriate controls at the scanning station. In either case, a means of encoding the translations is required to indicate stage location with respect to the origin of a scanner-based coordinate system.

The second alternative, coordinate measurement at a remote console as required for interactive operation, imposes the same functional requirements on the system, but implementation is more complicated. An indirect means of viewing the image and a reticle are required at the remote station, and the translation stages must be motorized so that they can be controlled remotely.

The third alternative, wherein coordinate measurements are derived in the computer by recognizing reference marks in the digital data and monitoring their location in the bit stream, requires that reference, fiducial, or reseau marks be digitized along with the image areas of the format. This automatic measurement mode could be used interactively, wherein an operator would select the image area and reference marks to be digitized from a remote console, or it could be used in conjunction with a manual positioning

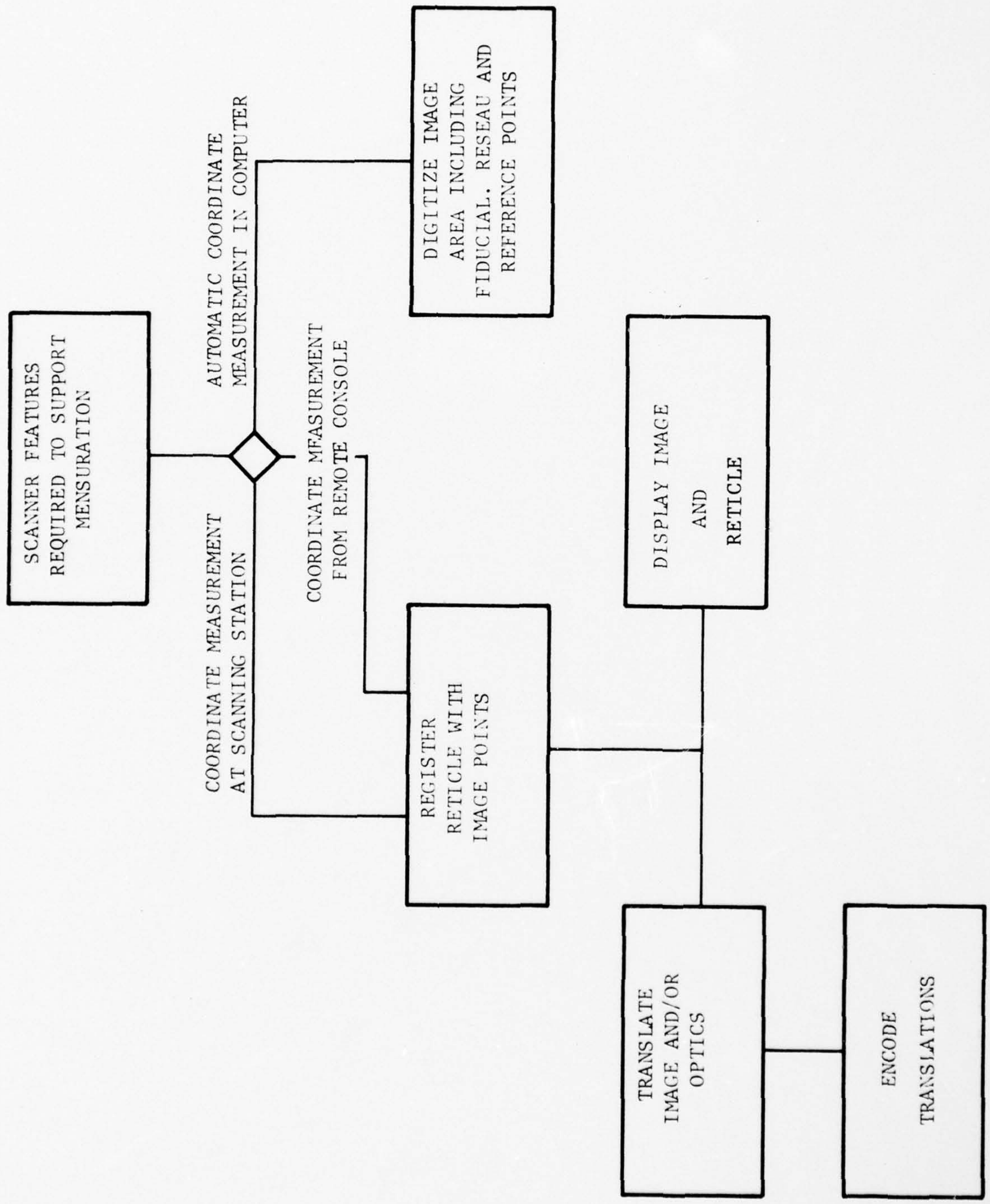

Figure 2-3. Alternative Modes of Coordinate Measurement

system where the operator selects the area to be digitized at the scanning station. Implementation requirements in this case are similar to those of the first alternative except that the capability to accurately position and register a reticle with image points (pointing) is not required. Similarly, with the interactive case, the accurate pointing is accomplished digitally in the computer, and the operator only needs the capability to approximately position the scanning window with respect to the selected image area or reference points from the remote console. In both cases, however, if the full format including reference points is not digitized, it is necessary to encode the motions of the translation stages so that interior orientation can be recovered eventually.

Either the interactive or automatic alternative would be required in a production environment, whereas the manual mode would satisfy most R&D requirements. The readily apparent exceptions are the development and evaluation of specific and detailed operating techniques for a production environment by the R&D laboratory.

Scanner capabilities imposed by typical stereo photogrammetric applications can be summarized as follows:

- Full format and selected window scanning capability
- Variable sampling interval and spot size
- Variable window size (number of pixels)
- Measure coordinates of fiducial and reference points
- Geometric linearity and repeatability
- Radiometric accuracy over dynamic range of input images
- Dual scanner or adequate digital storage capability

2.2.3.2 Feature Extraction

The extraction of terrain information and other topographic features from a variety of imagery such as conventional aerial photographs, multiband

images, and radar requires a man-interactive image processing system. The interactive capability would be used to selectively scan and digitize man-identified features from a small area in the image for extrapolation to the remaining part of the image and to other frames in the same strip of film. The interactive capability might also be used to generate a feature signature data base for subsequent use in the automatic classification and extraction of features from digital image data in a batch processing mode.

Both window scanning and full format scanning capabilities would be desireable in a scanner for this application. The window scanning capability would be most efficient for the latter case since the entire frame containing the sample feature need not necessarily be scanned. However, to satisfy the first case, the entire frame and possibly subsequent frames on a roll would be scanned either before or after the sample area of a feature had been digitized. This mode of operation, therefore, does not require a window scanning capability in the scanner because the sample selection could be accomplished on the display associated with the interactive capability by moving a digital window with respect to the entire frame of digitized image on disk, rather than interacting directly with the scanner. It does, however, require a full format scanning capability. The best operational mode for production purposes must be selected before a firm requirement can be established for the scanner. Nevertheless, for the purpose of comparing alternative technologies, it will be assumed that the scanner should have a full format and window scanning capability.

Other requirements imposed by this application include:

- Capability to vary resolution to accommodate different input resolutions and preserve operating economy.
- Ability to accurately quantize the image over the entire dynamic range of the input material.
- Possibly, the ability to rotate the scanner so that it can be aligned with dominant feature texture.

2.2.3.3 Feature Positioning

There are essentially two ways to perform image rectification and ortho-rectification in a digital computer:

- Perform an output-to-input space mapping, wherein the locations, in the input image, of a regular matrix of points in output image space are computed.
- Perform an input-to-output space mapping, wherein a regular matrix of points in the input image are projected to their rectified or ortho-rectified positions in the output image.

The former is usually preferred for several reasons, the most important of which are:

- The coordinates of the output points are implied by their locations in the output bit stream; therefore, only density values need be accommodated.
- A regular matrix of uniform spots on the output side of the process is preferable, if the output is to be a hardcopy image, because recorder implementation is less complex.

With this preference in mind, there are two ways in which hardcopy images can be converted to digital form in support of the rectification process:

- Scan and digitize a regular matrix of points on the input image.
- Perform an irregular scan of the input image under computer control.

In the first case, several lines of points must be stored in a buffer (the number is dependent on acquisition geometry) and the search for the locus of points (resampling) required to produce an output line is performed in the computer. In the second case, the computer directs the scanner to the appropriate points needed to fill an output line, thereby eliminating the buffer and digital resampling requirements. However, scanner implementation would be far more complex to achieve the same accuracy at the same speed. Furthermore, the buffer requirements are eliminated only when processing images

that are originally in hardcopy forms. If no conversion of input images is required, as is the case with electronic sensors, the buffer will be required anyway. Therefore, a full format scanning capability providing a regular matrix of points is most appropriate for the feature-positioning application if high-speed operation is important. The following capabilities are also required:

- Vary spot size and spacing to be commensurate with the different resolutions of various input images, output requirements, and operating economics.
- Measure coordinates of fiducial or reference points to establish interior geometry of digitized image.
- Accurate quantization over full dynamic range of input image.

2.3 SUMMARY OF FUNCTIONAL REQUIREMENTS

In summarizing the functional requirements of an image digitizer, we refer to Figure 2-1, Basic Functional Requirements of an Image Digitizer, and Figure 2-3, Alternative Modes of Coordinate Measurement. Based on the preceeding application-oriented discussion, the functional diagrams in these figures should be expanded in the areas shown in Figures 2-4 and 2-5.

Figure 2-4 addresses the positioning function, which involves the orientation of the scan head with respect to the input image. It assumes that the desired image area has been located either by visual inspection of the displayed image or by analytical means in a preprocessing step. The figure shows two alternative modes for achieving the desired orientation: automatic orientation and manual orientation. Both modes require that the image or scan head be translated and rotated. The manual mode also requires that the image be displayed for viewing, whereas the automatic mode does not, except as a check on the automatic operation. Instead, a means of entering the desired coordinates of the origin of scan and the angular orientation of its axes is required, along with methods of comparing these inputs to current stage position and orientation, and deriving translation and rotation drive commands.

Figure 2-5 addresses the scanning function. As discussed in the previous section, it is desireable to scan in two modes: a full format mode and window mode. In the window mode, the ability to vary the number of pixels in the window is also desireable. In both modes the spot size and sampling interval should also be selectively variable.

Control functions for an image scanner are shown in Figure 2-6. Within the context of the proceeding discussions it is self-explanatory.

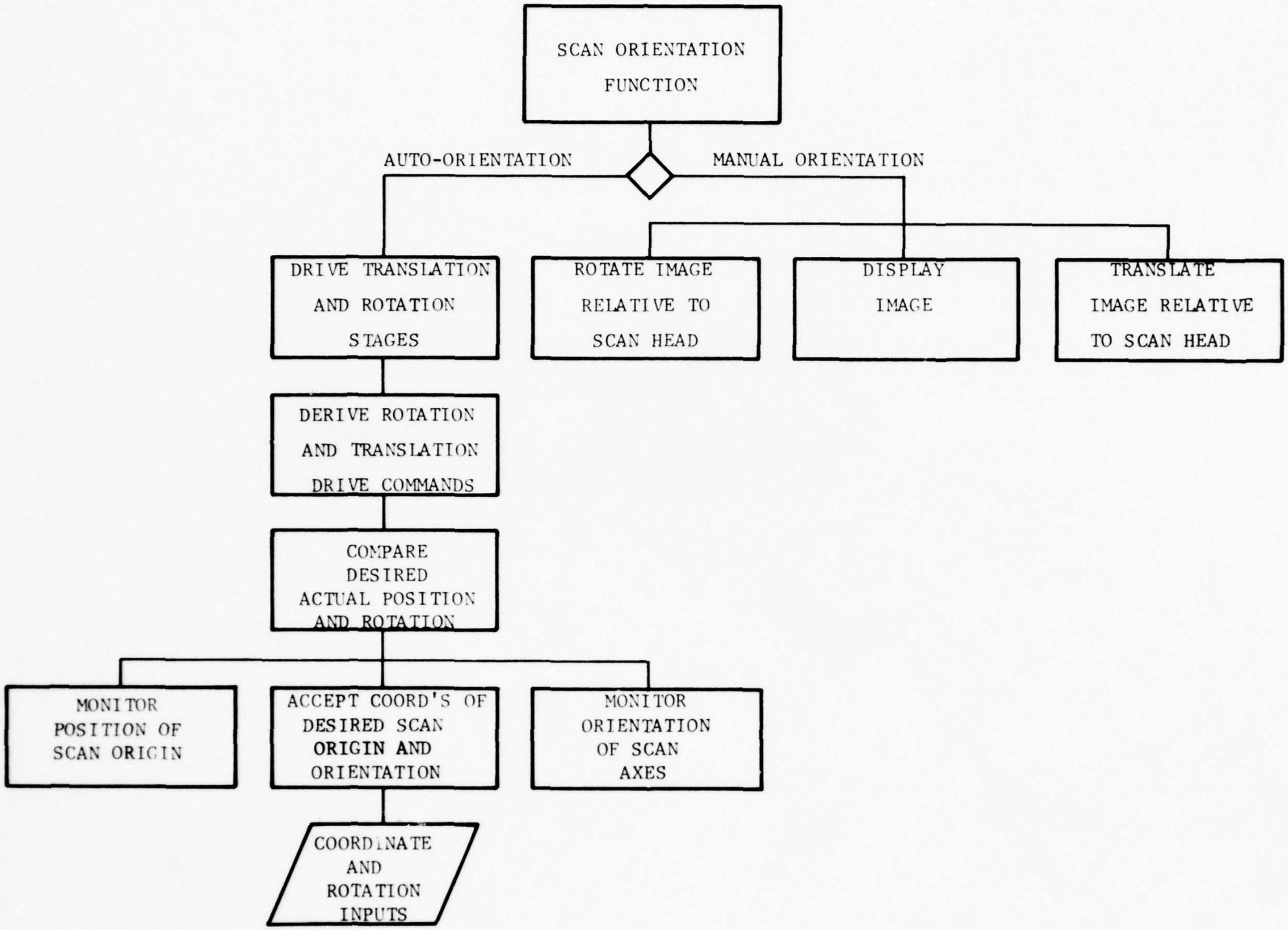

Figure 2-4. Functional Requirements for Scanner Orientation Alternatives

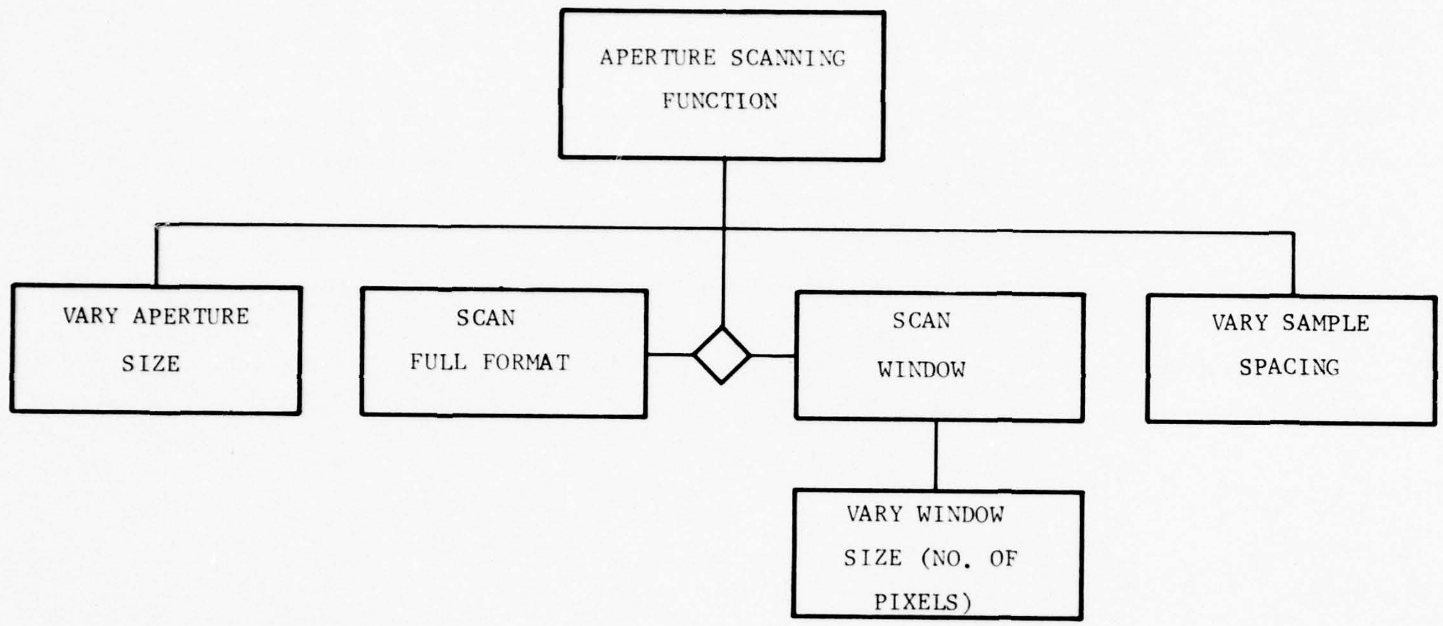

Figure 2-5. Functional Requirements Associated with Aperture Scanning

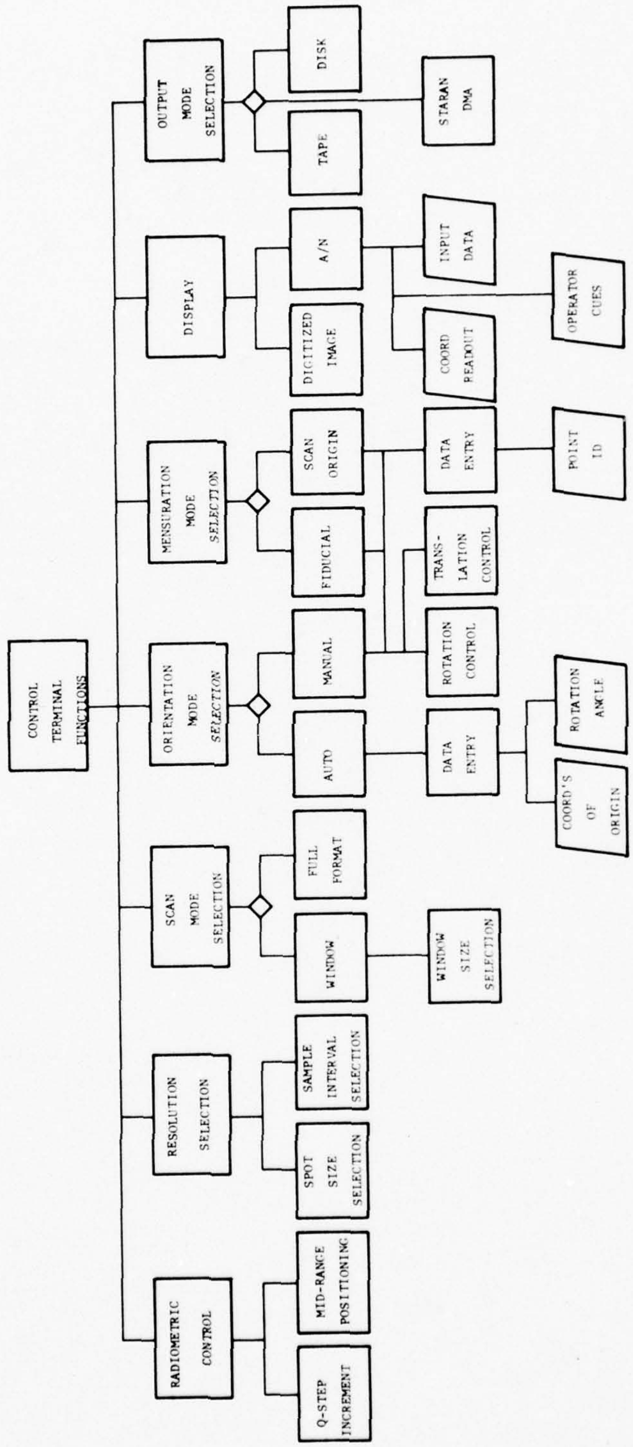

Figure 2-6. Control Functions for An Image Scanner

2.4 OTHER PERFORMANCE CONSIDERATIONS

Based on the previous discussion of functional requirements imposed on the scanner because of the applications for its digital output, it appears that the major performance criteria that the different technologies should be evaluated against include: format accommodation, resolution, data rates, geometric accuracy, radiometric accuracy, and dynamic range.

2.4.1 Format Accommodation

The scanner should accommodate image formats up to 230 x 230 mm on film in widths up to 242 mm in two different scanning modes: a full format mode, and a window mode, wherein an n by n pixel window can be selectively positioned anywhere within the format and also be rotated with respect to the picture coordinate axes as desired. The value of n should also be selectively variable up to a value of 2000 in the window mode.[2]

2.4.2 Resolution

The resolving power of the scanning system should be equal to or better than the resolution of the input images. Since input resolution will probably vary over the range of 20 cycles/mm to 100 cycles/mm, the capability of varying the scanning spot size at the film plane over a 5:1 range should be provided. Futhermore, since valid digitizing may be executed with no less than 2 samples per information cycle, the system should be capable of varying the size of the footprint at the film plane over a range of 5 micrometers to 25 micrometers. If oversampling is required, the capability of scanning with spot sizes ranging from 2.5 micrometers to 12.5 micrometers would be desireable. This, of course, quadruples the number of pixels that must be processed for a given area of input image, and operating economics need to be considered with regard to the gains anticipated for a given application, if any, from oversampling. It is also desireable to selectively vary the sample spacing.

Major considerations in comparing the various technologies should include:

- The minimum useable spot size, maximum number of pixels per line, and maximum number of lines per raster that are achievable with each.
- How difficult it is to vary spot size and sample spacing.

2.4.3 Data Rates

Speed requirements are another parameter which must be given careful consideration relative to the operational needs of the user. A production type of facility will need a scanner that can digitize images at a very high rate, while in a R&D environment the speed may be relatively unimportant. To be compatible with current and planned data transfer capabilities, the scanner should be capable of putting out digital data at, at least, 0.75 million pixels/sec. Since the DIAL System has the potential of handling rates up to 3.7×10^7 pixels/sec with special-purpose interfaces, scanner technologies offering high-speed capabilities are particularly attractive.

2.4.4 Geometric Accuracy

Mapping applications for a scanner impose severe accuracy and precision (repeatability) requirements. The ability to relate pixel space to image space (an orthogonal coordinate system in each frame of imagery, usually defined by reference or fiducial marks along the edges of the format) to an accuracy of approximately 3 to 5 micrometers is required. Linearity and orthogonality are important considerations for geometric precision.

2.4.5 Radiometric Accuracy and Dynamic Range

Since the primary function of a scanner system for the applications discussed is to convert images on film into digital form, the accuracy of quantization that a technology is capable of over the dynamic range of the anticipated inputs is an important evaluation parameter. Although there are high-contrast images with a 1000:1 dynamic range, typical continuous-tone images acquired from aerial platforms encompass a density range from 0.2 to 2.5

density units. Consequently a system capable of accommodating a 200:1 dynamic range will, in all probability, suffice for the type of inputs of interest for mapping applications.

It is generally accepted that at least six bits (64 levels) of intensity quantization are necessary for a acceptable representation of a continuous-tone image.[3] Furthermore, the film granularity noise associated with second- and third-generation duplicate images typically available as input to map production processes limits meaningful quantization to 8 or 9 bits, depending on resolution. Therefore, the technology should be able to provide at least 6-bit encoding but need not exceed a 9-bit capability.

In Section 3 different technologies for implementing scanners will be described briefly. In Section 4 some of the most applicable technologies will be compared based on the considerations discussed in this section.

SECTION 3

TYPES OF SCANNERS

3.1 GENERAL

All image scanning and digitizing systems consist of certain basic elements (see Figure 3-1). A variety of technologies can be applied in the implementations of some of these basic elements to achieve the performance required for specific spplications. In particular, alternative methods of implementing the illumination, detection, and deflection elements place scanners into different categories. Implementation of the focal surface assembly and the signal processing electronics generally are dictated by the technologies used for illumination, detection, and deflection. This is also true of the command and control subsystem, but to a lesser degree.

Scanners can be grouped into three classes based on either the technology used to illuminate the input or the method of detecting the energy transmitted by uniformly illuminated input. The three classes are referred to in Figure 3-2 as:

- Electronic Scanners - which may use cathode ray tube (CRT) devices, vidicon type imaging devices, or image dissector tubes.
- Solid-State Scanners - which may use charge-coupled devices (CCD's), charge injection devices (CID's), charge-coupled photodiode devices (CCPD's), and self-scanned photodiode devices (SSPD's).
- Electro-Optical Scanners - which may use lasers, light emitting diodes, or conventional lamps as a source of illumination.

These classes are further divided in Figure 3-2 according to the technology used to scan the sampling aperture over the area of the input to be digitized. The secondary classification categories include:

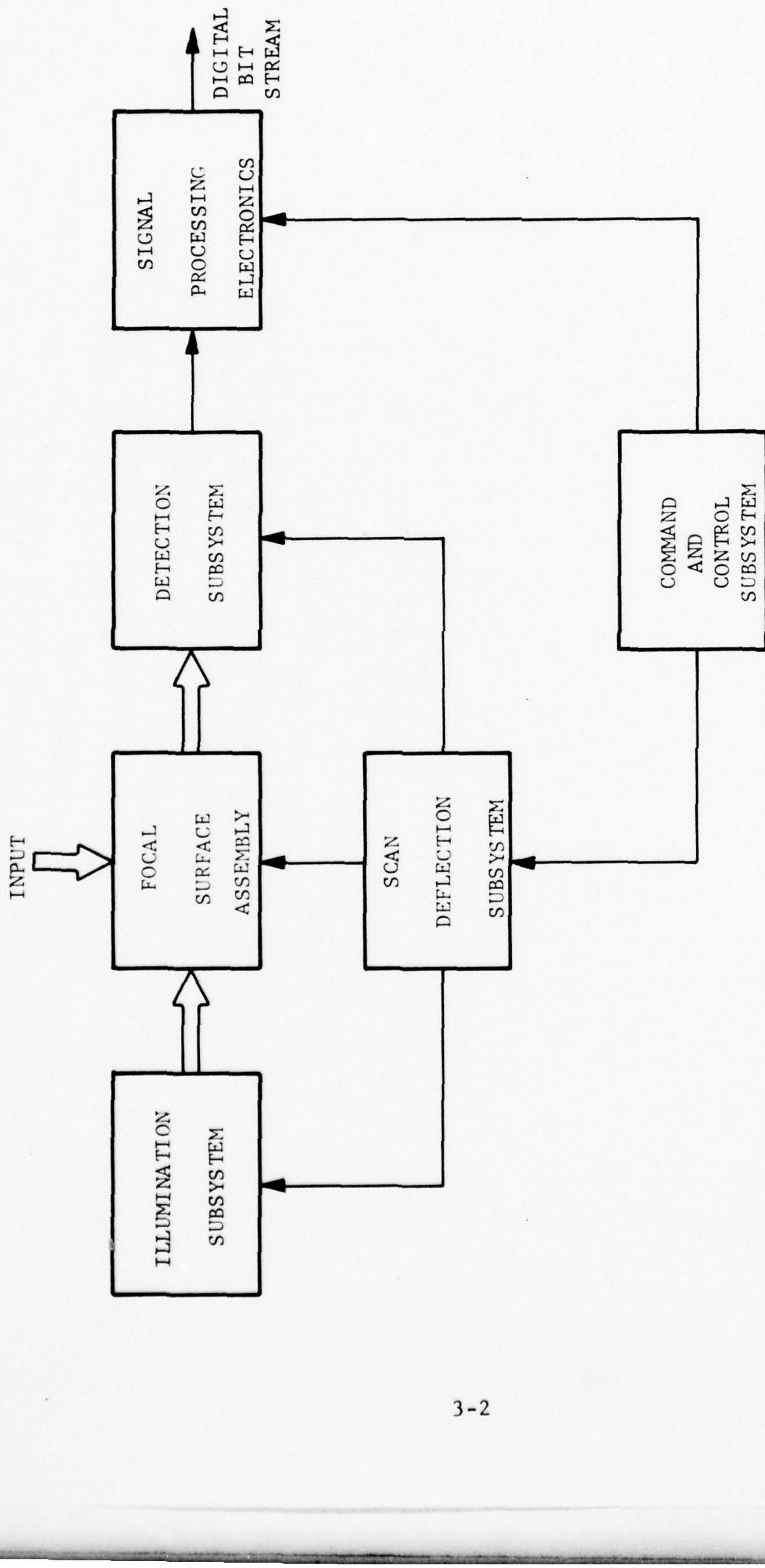

Figure 3-1. Scanner System Elements

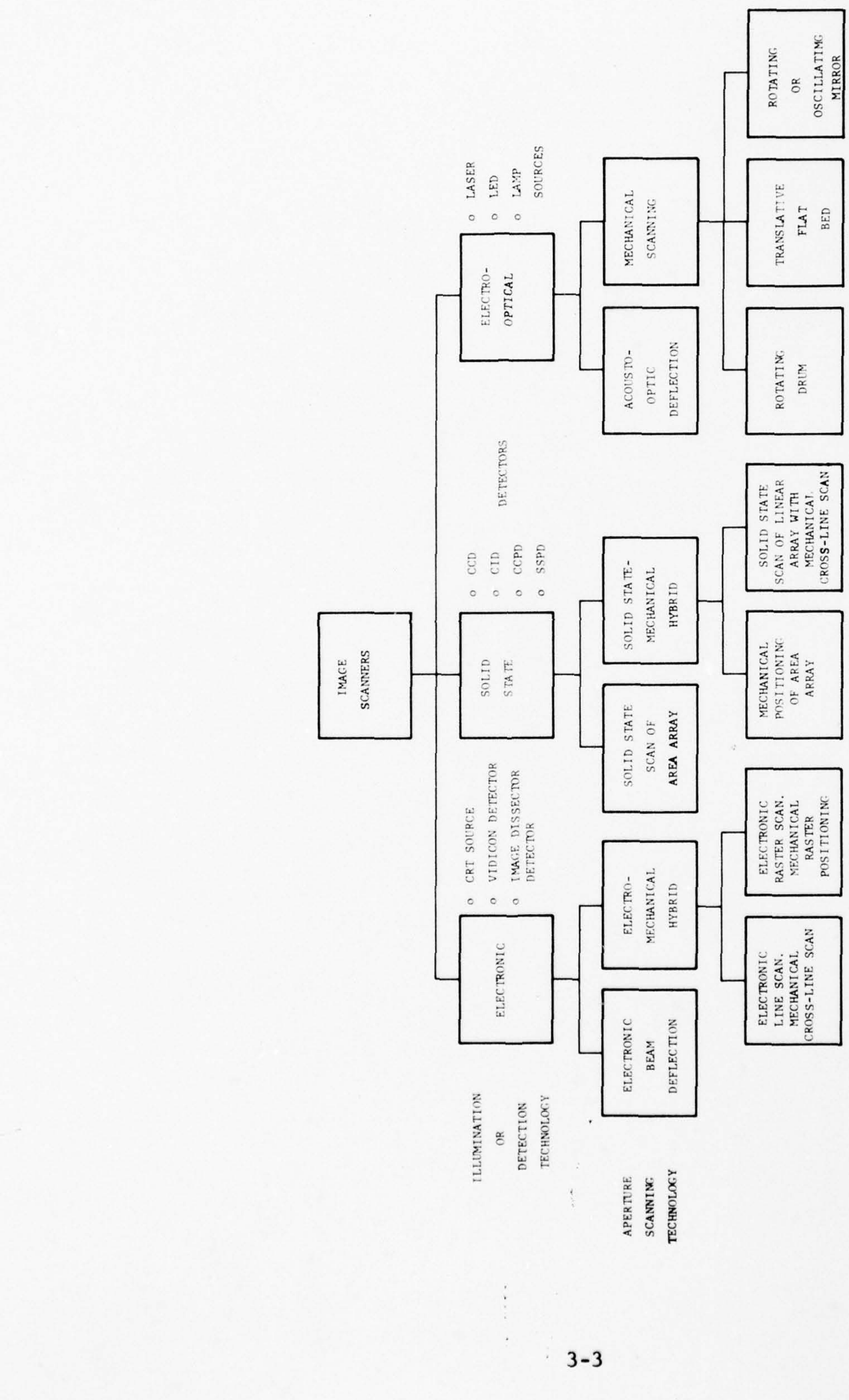

Figure 3-2. Classification of Image Scanners by Technology

- Electronic beam deflection
- Hybrid scanning, using electronic and mechanical techniques
- Solid-state scanning
- Hybrid scanning, using solid-state and mechanical techniques
- Acousto-optic beam deflection
- Mechanical scanning

A brief discussion of each scanner type is included in the following paragraphs.

3.2 ELECTRONIC SCANNERS

In electronic scanning systems, light transmitted or reflected from an illuminated image is projected onto a photosensitive surface which produces an electrical signal related to the variations in light intensity reaching the surface. The signal is then processed, sampled, and passed through an A/D converter to quantize it and produce a digital bit stream. The electronic scanners discussed in this report use cathode ray tube devices, vidicon type imaging tubes, and image dissector tubes as major elements of the system.

Some limitations of electronic scanning systems, compared to electro-optical systems, involve problems of beam defocus over the flat image plane, pincushion distortion, spot halo, and relatively low signal-to-noise ratio. In general, the linearity is limited to 1 to 2 percent. Resolving power of this type of system is also lower than with an electro-optical device as the signal-to-noise ratio is generally significantly lower. However, the digitization speed of some of these instruments can be high, up to several frames per minute at the lower resolution levels.

The useful dynamic range of these instruments is limited to about 0 to 2.5 density units.[3]

3.2.1 Cathode Ray Tube Scanners

The heart of the CRT-type scanner is the CRT. It serves as the source of illumination and at least part of the deflection subsystem. A photosensitive device for the detection subsystem is required to complete the basic elements of a CRT scanner (see Figure 3-3).

The CRT is a vacuum tube in which a finely focussed beam of electrons is made to impinge upon a light-emitting material (phosphor) deposited usually on a flat face of the CRT. The beam is deflected across this phosphor by electrostatic or magnetic means in a manner determined by the waveforms supplied to the controlling device. The intensity of light emitted is proportional to the current in the electron beam, which is controlled by a separate electrical control.

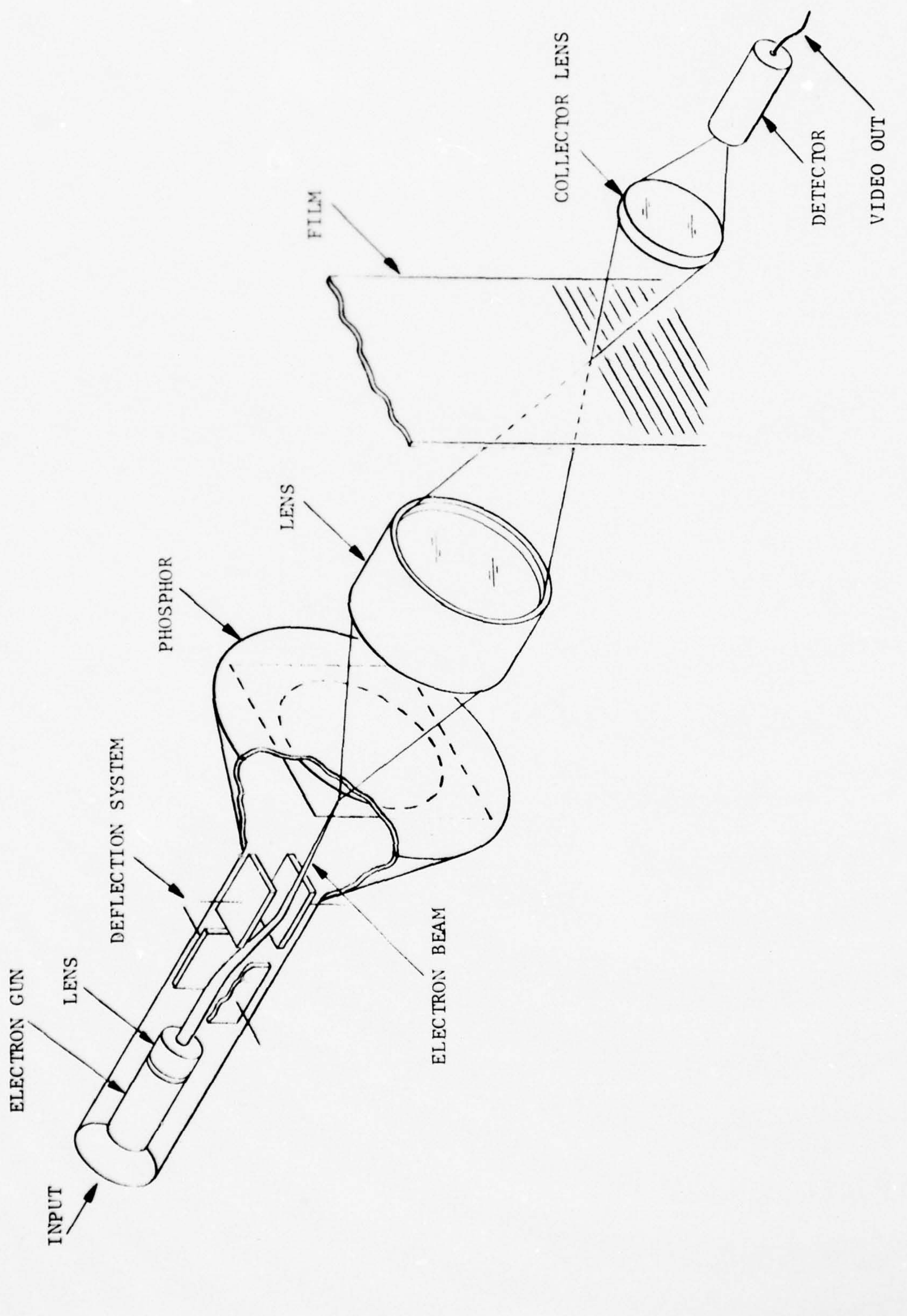

Figure 3-3. Basic CRT Scanner

Light emitted from the phosphor is then collected and focussed directly onto the film to be scanned. Light passing through the film in the scanner is collected and focussed on a photodetector, which converts the variations in transmitted light (density of film) into an electrical signal.

The CRT continues to provide satisfactory and, in many cases, superior solutions to many scanning problems. The principal attraction of the CRT is that it not only provides its own light source, but scanning flexibility as well. This flexibility is derived from the almost complete randomness of the spot positioning and the high speed at which this randomness can be employed. The inertialess beam thus places the limiting factor, as far as scan flexibility is concerned, on the drive circuitry of the deflection system. This means that the CRT scanner is an ideal device for applications where high-speed random-access spot positioning is required, particularly where computer-controlled system interaction is valuable.

With regard to implementation options for the aperture scanning subsystem, CRT systems fall into either the all-electronic beam-deflection category, or the electro-mechanical hybrid category. The former requires a two-axis deflection system that can be used to scan a uniform matrix of spots (raster) or generate an irregular (random) scan under computer control. Two different hybrid scanning approaches (see Figure 3-4) can be implemented with CRT systems:

- Mechanical stages providing motion along two orthogonal axes can be used to position the CRT with respect to the image format to be scanned, and two-axis electronic beam deflection used to generate the uniform matrix of sampling spots at the localized area.
- Single-axis electronic beam deflection can be used to repetitively generate a scan line while cross-scan motion is provided by a linear-motion-translating mechanical stage or a film transport.

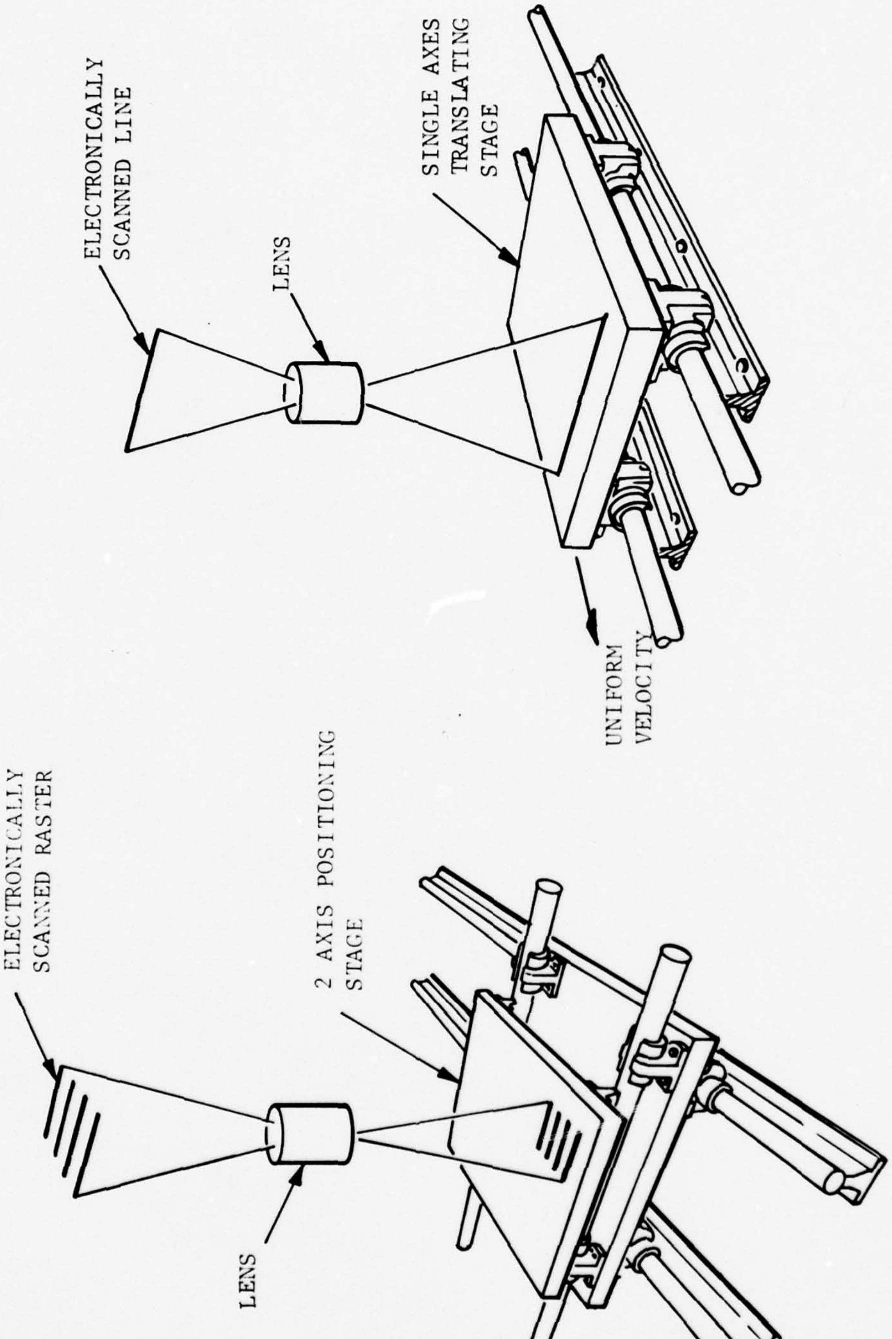

Figure 3-4. Two Mechanical Hybrid Scanning Approaches

Although not widely used, it is also possible to vary the effective CRT spot size by defocussing or by high-speed dither (jitter). This feature could be valuable for handling scale-factor changes.

Variations of the CRT device include fiber optic faceplates (see Figure 3-5), which can be used to couple light directly to film with no intervening optics.

One of the difficulties that has plagued CRT scanners has been the signal-to-noise ratio. However, with the development of improved phosphors, this problem has been reduced, and for many applications, the CRT produces sufficient light output without requiring high beam current. In developing high-resolution CRT scanners, it is necessary to use a low beam current in order to maintain a small spot size. Unfortunately, this low beam current results in a lower brightness spot, which in turn limits the speed at which the spot can be scanned and still achieve an adequate signal-to-noise ratio. Ultimate limits of a CRT system are about 7000 to 8000 pixels per line.

However, a more practical limit for a reliable and workable piece of hardware is about 4000 pixels per line.

The CRT systems also have other limitations. For one, spot shape varies with the location in the scan because of beam landing error; i.e., the angular deflection of the beam causes the spot shape to vary from circular at the center of the CRT to ellipsoidal at the edges. To minimize this error, the deflection angle should be kept small. The linearity of a flying spot scanner is usually limited to about 2 percent; correction techniques to improve this factor to about 0.05 percent exist, as do ones for focus, astigmatism and pincushion distortion. Incorporation of these techniques increase costs as well as performance.

In summary, CRT scanners may vary widely in price, depending on the care and quality put into the device. They can give excellent resolution at the expense of speed and scan line length, and are a good choice for the appropriate application.

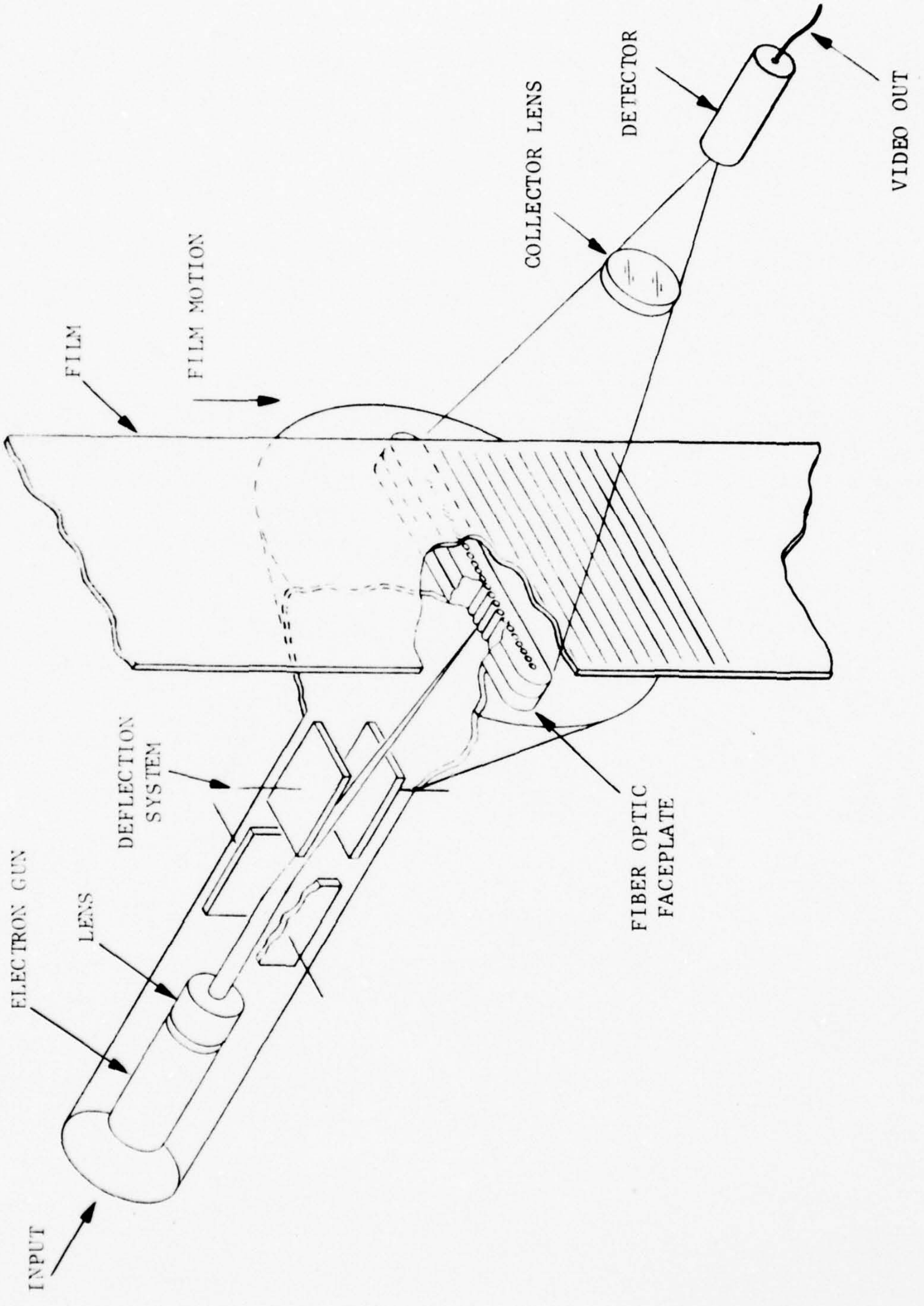

Figure 3-5. Fiber Optic CRT Scanner

3.2.2 Image Dissectors

An image dissector is a vacuum tube with one end, the photocathode, coated with a material that converts incoming photons into electrons. It is a non-storage type of camera tube and does not employ a scanning beam. In reality, it is nothing more than a photomultiplier with a small, electronically-movable photocathode area. The operating principles are illustrated in Figure 3-6.

An electron lens accelerates and focusses all electrons emitted from each point on the photocathode to a corresponding single point in the image plane containing the dissecting aperture. The resulting electron image is analogous to the image on film, because the current density at any small area on the image plane will be proportional to the light intensity incident on the corresponding area of the photocathode. The entire electron image is electronically deflected or repositioned on the image plane to cause any small part of the electron image to pass through the aperture at the center of the image plane.

Consequently, at any instant of time the aperture samples the photoelectrons from a small, well-defined area of the input optical image incident on the photocathode. An electron multiplier behind the aperture multiplies only those electrons passing through the hole. Multiplication is by a large factor, typically 10^5 to 10^7, and the resulting output signal emerges as a current in the output anode circuit.[5] This output signal is converted to a digital number that is proportional to film transmittance at a specific sample point (pixel). Successive deflections, which can be digitally commanded through a D/A converter, produce digital values for additional pixels and may produce a raster scan pattern if desired.

The resolution capability of an image dissector is determined primarily by the size and shape of the dissecting aperture and the associated electron optics. Theoretically, the potential for as many as 8000 pixels per image diagonal exists, but noise tends to be a problem unless long integration times are used.[7] Furthermore, the actual magnitude of the inherent resolution limits varies sharply with such factors as:

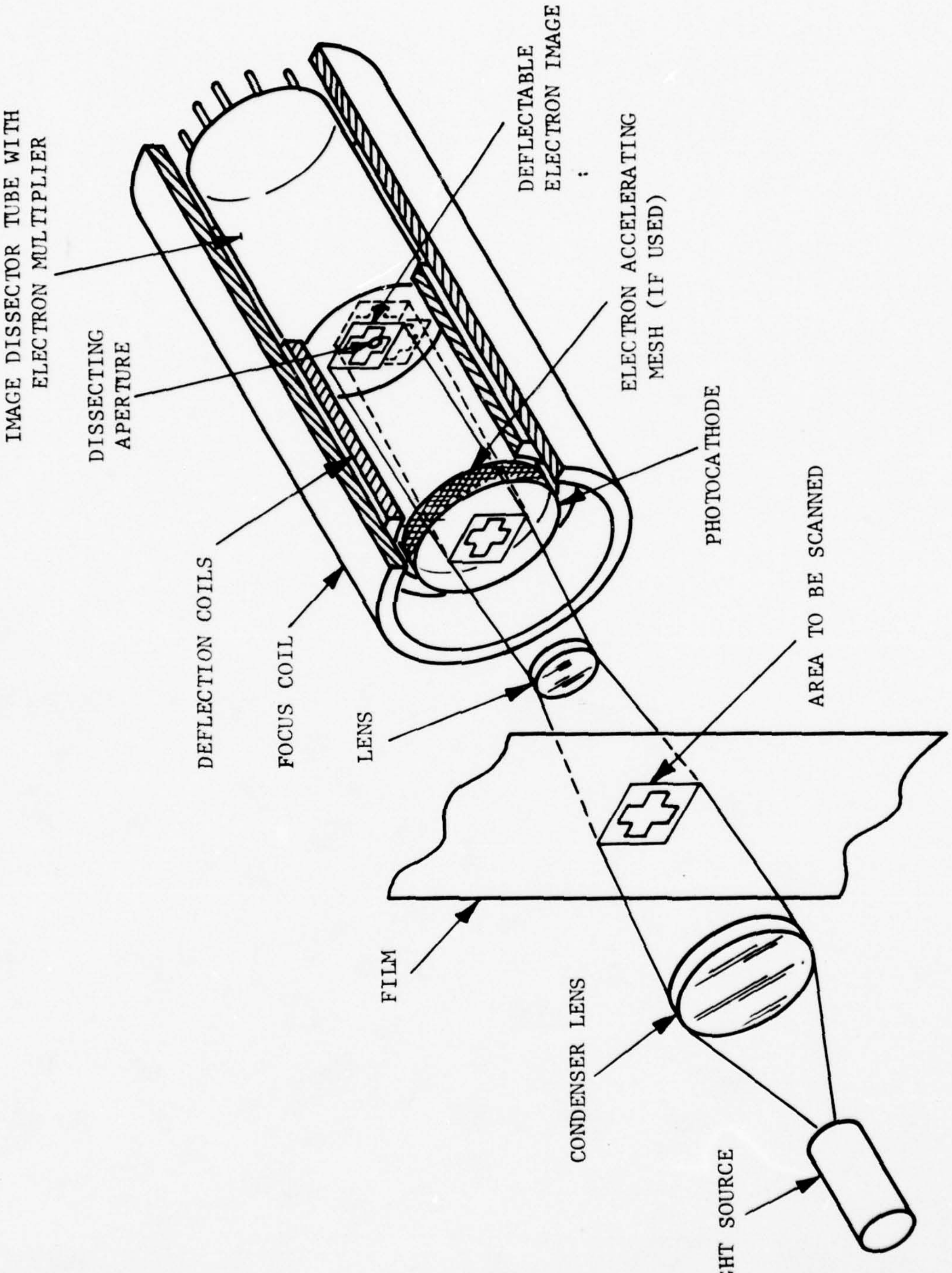

Figure 3-6. Image Dissector Scanner Schematic

- The type of focussing used (with magnetic focussing usually being markedly superior to electrostatic focussing).
- The spread in emission energy of the photoelectrons as determined by the wavelength of the input flux and the type of photocathode.
- The electron optical aberrations introduced by deflection.
- The degree of dynamic focussing used, i.e., the extent to which focus is electronically readjusted in synchronism with scan.

Consequently, the theoretical potential does not get realized in practical systems. The estimated limiting resolution of a typical high-resolution tube such as the ITT F4052 Vidissector,* with a sufficiently small aperture and a matched deflection and focus coil assembly, dynamically focussed for minimum astigmatism, can be exptected to approach or exceed 50 lp/mm in the major portion of its useful image area (1.8-inch diameter). This is more than 4500 TV lines per image diagonal, at 30 percent peak-to-peak sine wave modulation.[6]

A resolution exceeding 20 lp/mm, or more than 2500 TV lines/image-diagonal, at 30 percent or better modulation over the image area is routinely achieved in actual measurements of the behavior of real F4052 Vidissectors having a 6×10^{-4} inch diameter aperture and including coil and optical system limitations. Within most of the image area, more than 4000 TV lines/image-diagonal can be observed with these tubes.[6] This approaches the resolution number predicted above on the basis of the known physical aperture size, but not at the predicted modulation.

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* An advanced line of magnetically focussed magnetically deflected image dissectors developed by ITT. These tubes involve the addition of an electron-transmissive metal mesh in close proximity to the photocathode, followed by an electric-field-free focus and deflection drift space, quite similar to the technique used in vidicon camera tubes (hence the name "Vidissector"). This gives them excellent electro-optical conversion properties (low distortion, high resolution, long life, etc). Vidissectors ranging in outside diameter from 1 inch (the F4012) through 1.5 inches (the F4011), 2.25 inches (the F4052) to 4.5 inches (the F4010) are presently available.[6]

As is the case with CRT scanners, image dissectors can be used in scanners employing all electronic deflection techniques or both hybrid techniques previously discussed.

Other advantages include its adaptable scan, linear output, and wide bandwidth characteristics. The image dissector can easily be switched on command from one scan mode to another. When in a simple raster or matrix scan mode where the basic deflection matrix contains, for example 2048 x 2048 positions, the scanner can be made to sample every other position, every fourth position or every eighth position to produce scanning matrices, or "windows," of 1024 x 1024, 512 x 512, or 256 x 256 points. Scanning can take place asychronously and rates can be computer-controlled.

The output from an image dissector is linearly proportional to the input flux over many orders of magnitude. Thus the image dissector can be used as a precision microphotometer and is useful in digitizing film transmittances for computer input. However, it has a low search mode (area scan) capability.

Since the image dissector wastes all image photoelectron information that does not happen to pass through its aperture at any instant of time, it is inherently less sensitive than "storage" type scanning tubes, such as the image orthicon and vidicon, for the wide field scan mode, where a large number of image elements must be scanned. Typically, 1.5 to 2 minutes are required to scan a 2048 x 2048 matrix of points.

Also, the input-output responsivity of an image dissector will generally vary, at least by a small amount, from one point to another over the viewed field. If the change is gradual, it is called "shading," with variations within ±10 percent or so over the image field being typical.[8] More serious, in many applications, are the rather sharp variations, called blemishes, that can occur within one or more picture elements. The number and amplitude of these blemishes are often an individual tube-sample characteristic. However, as in other TV camera tubes, blemish numbers can be kept small by proper quality control during tube manufacture. Other undesireable characteristics of image dissectors are discussed below.

Off-axis defocussing is a problem. When a peripheral image element is deflected into the aperture of a dissector, the effective aperture size and shape, and the rise distance may change. This can be, and commonly is, correctable in practice by applying a dynamic focus signal to the tube focus circuits in synchronism with the deflection. Such dynamic focus signals are usually easy to apply. The residual defocussing, after correction, is partially limited by tube design and partially by the external focus and deflection coil design.

Some image distortion (non-linearity between the aperture position and the applied deflection signal) occurs in all image dissectors, ranging from markedly noticeable magnitudes in simple diode electrostatic systems to almost negligible magnitudes in the Vidissector design. Simple pincushion or barrel distortion can be compensated for by appropriate correction signals applied to the deflection circuits. Some non-radially-symmetric distortion occurs in all practical tubes due to small asymmetrics in tube construction, but can usually be kept below 1 to 2 percent. Radially constant image rotation can be corrected by proper placement of the deflection coils (or plates), but non-constant rotation (i.e., spiral distortion), if present, is not readily corrected. Spiral distortion is almost always below 1 to 2 percent in practical dissector designs.[8]

Although the image dissector has no gear and bearing backlash problems, there can be an equivalent problem introduced by hysteresis in the deflection circuits (failure to reproduce exactly the same aperture position for a given applied deflection signal). This can effect repeatability, from a coordinate measurement and photometric measurement point of view. In magnetically focussed tubes, it can be caused by magnetic hysteresis in the magnetic core material or magnetic shielding material. In electrostatically focussed tubes, it can be caused by electrostatic charging of internal insulator sufaces. With proper tube and coil design, these effects can often be reduced to negligible values.

Photocathode fatigue is another problem here. With continuous intensive current density loading of a photocathode, it is possible to gradually reduce its responsivity, especially in the red region of the spectrum. Therefore, a means of calibration and compensation must be built into the scanner.

The high gain properties of electron multipliers make them inherently sensitive to the magnitude of the applied voltage and to small chemical and physical changes in the dynode surfaces. Thus the applied voltage should be regulated, and the temperature held within reasonable limits, such as ±10°C, to achieve stable gain.

Despite their lack of picture information storage and their resultant reduced S/N ratio, image dissectors are nearly ideal devices for some applications. They are linear in response over many orders of magnitude, capable of directly observing the fluctuations of the input electron image, and can be used over a wide range of scan rates and resolving powers. Consideration should be given to the possible use of an image dissector for any image scanning process, such as computer-directed random image access, which does not require or cannot tolerate image information storage.

3.2.3 Vidicon Scanners

In a vidicon system, the light reflected from or transmitted through an image on film impinges upon the photoconductive target of the vidicon, as illustrated in Figure 3-7. The variation in the local charge concentration due to the image on the surface is converted into a video signal by repeatedly scanning the photoconductive surface with an electron beam.

An imaging device in this class has an electron gun, which produces the electron beam, and a magnetic or electrostatic deflection mechanism for controlling the landing location of the beam on the target.

The target in a vidicon is a photoconductive mosaic deposited upon a transparent metal film (the signal plate). Light passes through the signal plate and strikes the photoconductive mosaic, changing its resistivity. When the

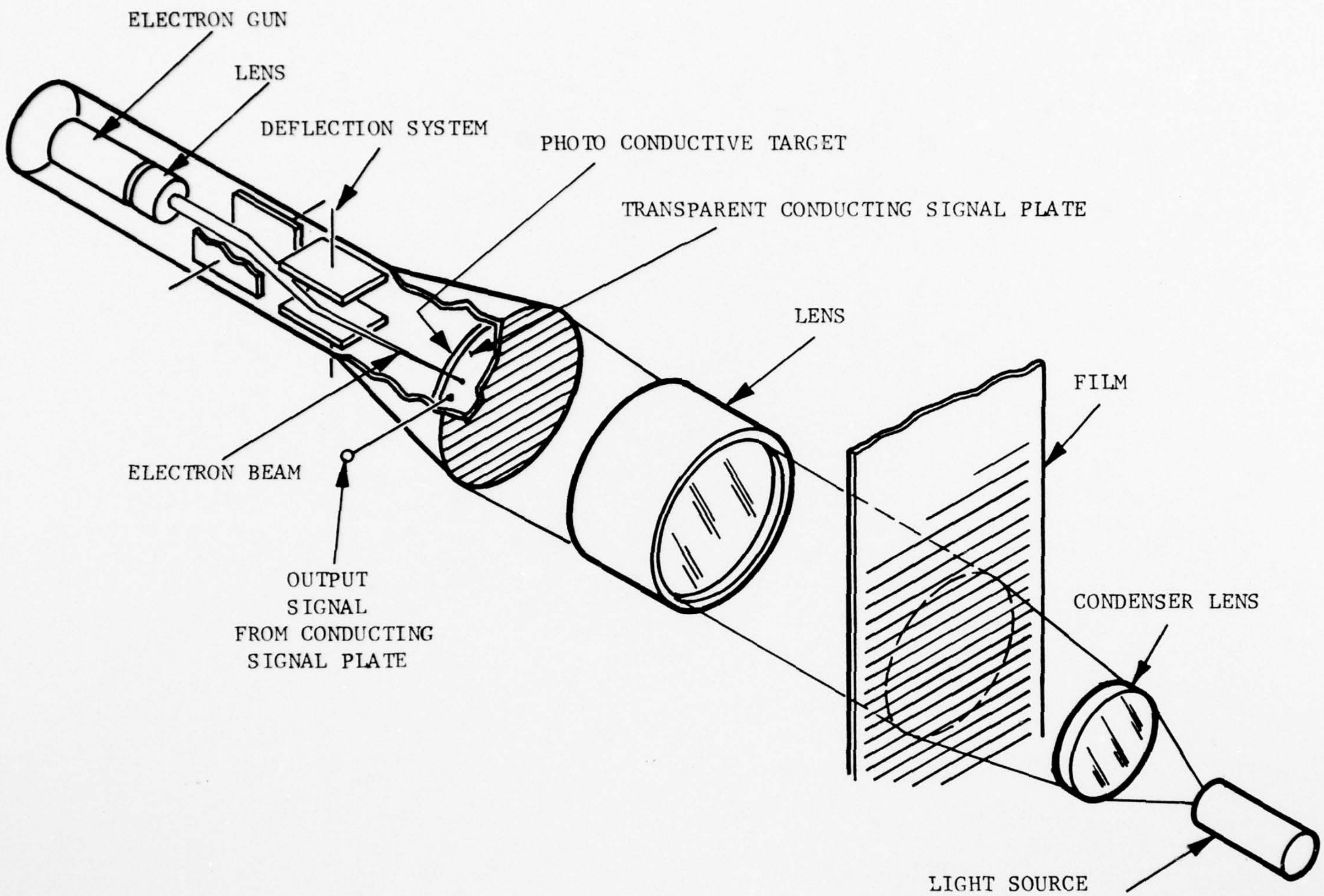

Figure 3-7. Schematic Representation of Vidicon Scanner

scanning electron beam strikes a particular piece of the mosaic, the current passing from the beam through the mosaic to the signal plate will be proportional to the amount of light striking that piece of mosaic.

Since the location of the beam is known for each instant of time, the output-current-versus-time function is directly related to the input-intensity-versus-position function.

The signal electrode is operated at a positive voltage with respect to the back side of the photoconductor, which operates at the cathode (near zero) voltage. In operation, the scanning beam initially charges the back side of the target to cathode potential. When a light pattern is focussed on the photoconductor, its conductivity increases in the illuminated areas, and the back side of the target charges to more positive values. The electron beam then reads the signal by depositing electrons on the positively charged areas, thereby providing a capacitively coupled signal at the signal electrode.[5] This signal is transmitted through a video amplifier and signal conditioner to sampling and quantizing electronics.

A silicon vidicon is very similar to a vidicon except for the nature of the target. In a silicon vidicon, the target is a silicon wafer that has had an array of diodes diffused into one side. The diodes are located on the side of the wafer facing the electron beam. A potential applied to the wafer substrate effectively back-biases the diodes and produces a depletion region in the vicinity of the junction. As photons enter the wafer, they collide with atoms and produce electron-hole pairs. The minority carriers diffuse to the depletion region and are swept out by the electron beam when it passes the diode, producing a current proportional to the number of photons that entered the depletion region since the last time the electron beam went by.

Silicon vidicons have a higher output current and a wider spectral response (extending well into the infrared) than conventional vidicons, and are virtually burnout-proof.[7]

The significant difference between the dissector and vidicon-like devices is the fact that vidicons are charge-storage devices, whereas dissectors are not. To achieve a reasonable signal-to-noise ratio, the device must allow a sufficient number of photons to hit the target to effectively average out the effects of shot noise. In the dissector, this is accomplished by leaving the electron multiplier active for a specific period of time (generally in the millisecond range). In the vidicon, photon generated charge is accumulated over the entire surface simultaneously for a period of time equal to one frame of scan (30 ms for U.S. standard televisions).

The charge accumulation effect causes the signal output amplitude to depend on both the incident light and the charge accumulation time. Hence, to remove the dependence on time, the vidicon must be scanned at a constant rate, precluding the use of random-access scanning.

The resolution of the RCA return-beam vidicon tube system is the highest of commercially available electronic sensors. It is available in two package sizes: 4-1/2 inch and 2 inch, having photocathode sizes of 50 x 50 mm and 25 x 25 mm, respectively, and providing approximately 4000 and 2000 element resolution, respectively, at a square wave response (contrast transfer function) of 50 percent. The limiting resolution of this tube is reported to be 10,000 TV lines; however, the large capacitance of the antimony-sulfide-oxysulfide target produces excessive image smear for moving scenes.[9]

The 4-1/2-inch RBV provides about twice the resolution of other vidicons including the slow scan Westinghouse WX 31958 Vidicon (Secondary Emission Conduction), and is approximately in line with the very high resolution CRT's such as the Westinghouse WC 31536P with about 4000 elements per scan (at 50 percent response) at 1μA beam current.

As with the other electronic scanners discussed, vidicon systems can employ all-electronic deflection (for areas limited to approximately 1500 x 1500 elements with most vidicon, and 4000 x 4000 elements with RBV's) techniques or both hybrid deflection techniques previously discussed.

Some of the disadvantages associated with vidicon systems include a relatively long lag, blooming, and variation in responsivity and geometric distortions.

If one focuses a television camera on a stationary object and then suddenly moves the object away, an image of the object can be seen to slowly fade away. This phenomenon is known as lag. The lag can be as long as 90 ms before the old image is completely gone.[7]

Lag is a function of the type of material from which the target is made, the energy distribution of the electron beam, and the physical geometry of the target. Silicon vidicons have a relatively long lag.

When an area of the target is exposed to very intense illumination, more carriers are created than can be swept out by the electron beam in one frame time. The excess carriers diffuse outward, causing an apparent enlargement or "blooming" of the bright region. This apparent enlargement distorts the picture and can have disastrous effects on scene analysis programs.

Blooming varies with the logarithm of the intensity. One way to deal with blooming is to change the tube's linear response to high-intensity light. However, this also destroys the tube's linear response characteristics.

Another technique which preserves the tube's linearity while still reducing blooming is control over surface recombination effects, and is achieved by ion implantation of a very thin region on the scene side of the substrate.[7]

The photoconductive surface of vidicons is, in general, not of constant thickness. Variations of this type cause the output signal to vary with a fixed input intensity according to geometric position on the tube face. Also, beam landing error, an effect caused by the variation in shape of the spot due to deflection angle, causes a varying geometric distortion, which is largest at the edges of the image.

Vidicons do, however, offer relatively high scanning speeds.

3.3 ELECTRO-OPTICAL SCANNERS

Electro-optical scanners use dual optical systems. The illuminating optics focus a regulated light beam upon the sample film, while the pick-up optics transfer the transmitted light or reflected light onto a photosensitive device whose current output is proportional to the input light intensity. The output signal is amplified, sampled, and passed through an A/D converter in preparation for storage in digital form. These systems utilize lasers, light emitting diodes (LED's) and the more conventional type lamps as sources of illumination. Referring back to Figure 3-2, they are grouped into two subcategories based on the means of implementing the scanning function:

- Acousto-optic beam deflection
- Mechanical scanning techniques

The latter category includes rotating drum scanners, translating flat bed scanners such as microdensitometers, and rotating or oscillating mirror scanners.

3.3.1 Acousto-Optic Scanners

Acousto-optic devices are very useful in laser scanning systems for a variety of functions. They can be used to modulate, deflect, focus, or shift the frequency of light. Of particular concern in this discussion are their deflection capabilities.

Since the angle at which an acousto-optic device deflects light is proportional to the frequency of the acoustical drive signal, they can be made to scan a beam by changing the frequency of the drive signal. This is done electronically, usually by employing linearly swept FM signals. Consequently, scanning speeds are flexible, with the highest speeds determined by the acoustic propagation time through the cell.

In general, these devices are limited to a one-dimensional scan, with between 1000 to 2000 resolvable spot diameters per line. Deflectors of this type that operate at frequencies up to 400 megahertz have been designed, built, and tested.[10]

The attractive features of these scanners are their high speed, lack of moving parts and small size. The problems include:

- Limited scan angle
- Limited power-handling capability
- Limited resolution
- Requirement of very high frequencies for deflection

There is work going on now to increase the resolution of the acousto-optic scanner to above the 1,000 to 2,000 elements/scan level, but as yet the techniques are not available in commercial products.

The Harris Corporation [10] has achieved higher resolutions by employing a technique that incorporates two acousto-optic devices (a beam deflector working in series with an acoustic-traveling-wave-lens device) to produce an extremely fast, high-resolution laser scanner that uses no moving parts, except to transport film.

The acousto-optic deflector forms approximately 1000 spots, which are imaged onto the traveling-wave-lens. This device is driven by an electronic pulse having the appropriate shape so as to cause the index of refraction variation in the acoustic media to approximate a thick lens, which reduces the spot size. The scanned beam from the first deflector is synchronized with the traveling-wave motion to scan the reduced spots, as illustrated in Figure 3-8. This laboratory model Traveling Lens Laser Scanner is reported to be capable of speeds greater than 10^8 pixels/sec and 10,000 line/sec with a resolution greater than 10,000 pixels per line.

The fundamental advantages of this type of system are:

- Large number of spots at high speeds are available with no moving parts. The pixel rate is the ratio of the acoustic velocity to the output spot size.

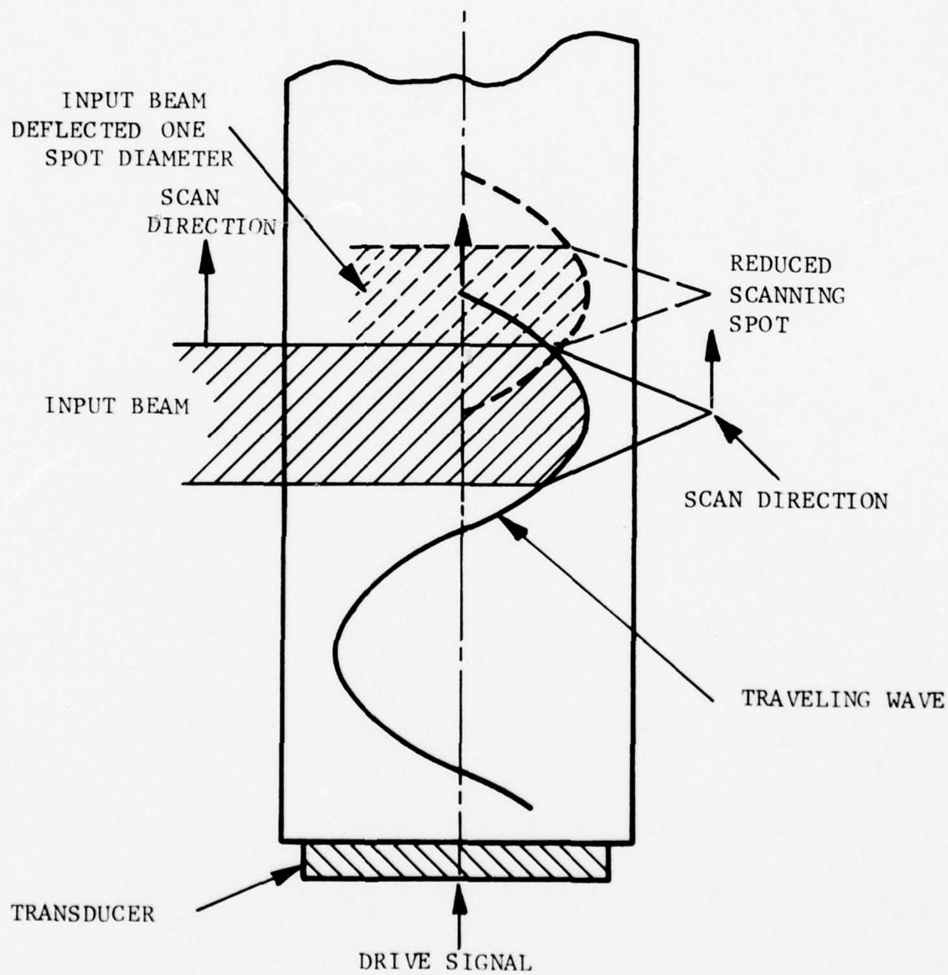

Figure 3-8. Acoustic Traveling Wave Lens Cell

- A flat field at the output is automatically attained, thereby eliminating the need for expensive field flatteners.
- Linearity, which is inherent in the traveling lens, is reported to be good; however, no quantitative data has been published at the time of this writing.

Some of the disadvantages include the following:

- The optical path length and number of optical elements required are both relatively large.
- System alignment could be a problem.
- There is an intensity fall-off in output at the margins of scan in laser beam systems deflected to the resolution limit with acousto-optic devices.
- Technology has not yet been implemented to the advanced state that other devices considered in this report have.
- Cost would be relatively high.

3.3.2 Mechanical Scanners

The electro-optic type scanners discussed in the following paragraphs employ mechanical scanning techniques such as rotating drums, translating flat bed stages, rotating or oscillating mirrors, and combinations of any two of the above. Rotating drum systems are discussed first.

3.3.2.1 Rotating Drum Scanners

One of the simplest scanner and printer configurations uses a rotating drum. This has been widely used in facsimile systems. In this configuration, the light source is focussed by a high-quality lens, such as a microscope objective onto the material to be scanned or exposed (see Figure 3-9). The material is mounted on the outside of a drum which rotates about its axis. Scan in one direction is accomplished by rotating the drum (and the material)

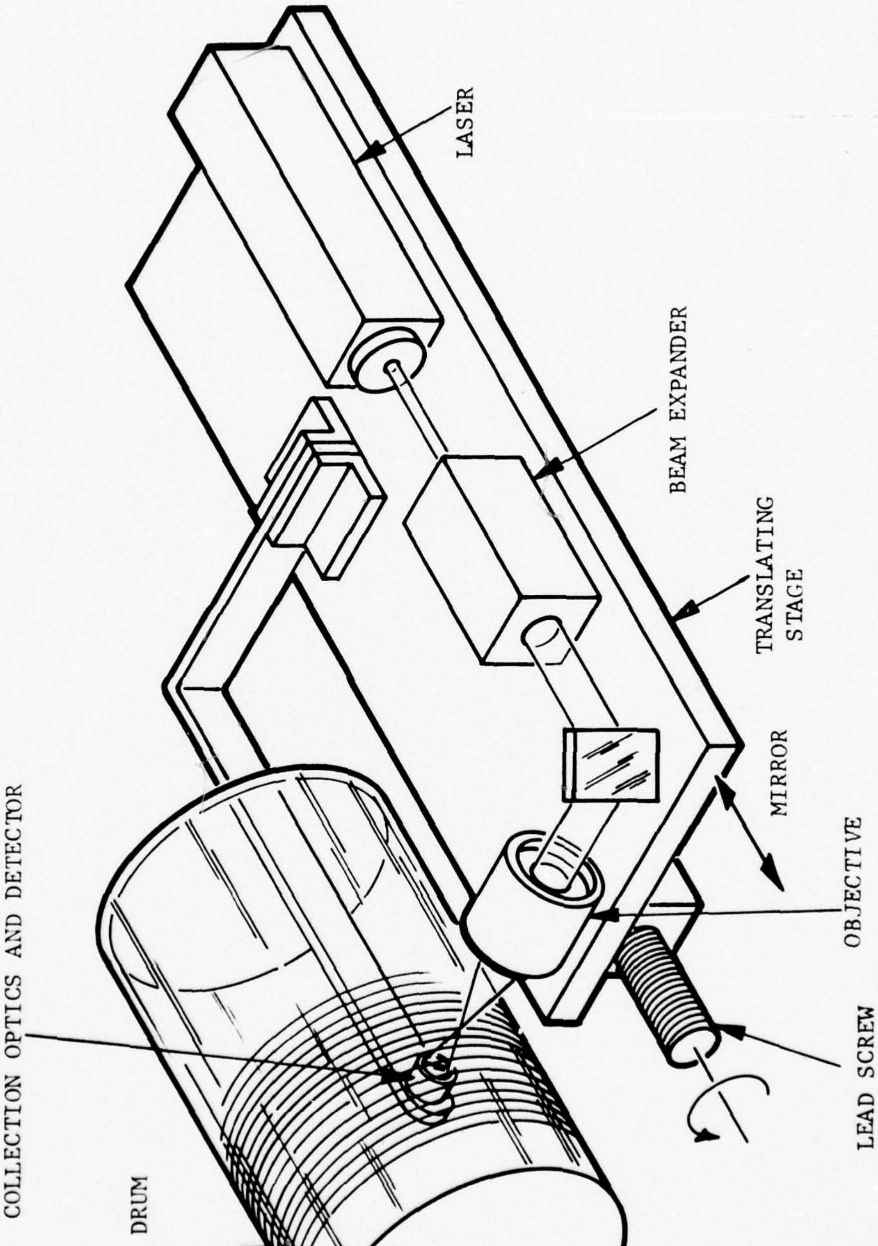

Figure 3-9. Rotating Drum Scanner

past the focussed beam. Scan in the other direction is accomplished by translation of the light source/lens parallel to the axis of the drum, or by translation of the rotating drum.

The optical system on rotating drum scanners is usually mounted on a u-shaped carriage that translates parallel to the axis of the drum. The illumination source, with its associated optics and apertures, is located on one portion of the carriage and travels either outside or inside the rotating drum. Pick-up optics, apertures and light detection element are located on the other arm of the carriage, which travels on the opposite side of the rotating drum. Directly connected to the drum is a rotary encoder used as a strobing clock pulse for points around the circumference of the drum. The optical carriage system is moved independently, along kinematic mounts, by a stepped or servo-controlled motor-driven lead screw. The output current from the detection element is amplified (usually logarithmically), passed through a sample-and-hold circuit and into an A/D converter, where the voltage proportional to the sampled image density is converted to a digital signal.

In Figure 3-9, a laser is shown as the illuminating source. However, any regulated lamp that can be made to provide equal illumination over the total aperture area at the surface of the film being scanned can be used. Two different illumination and optical approaches are illustrated in Figure 3-10. One employs a laser and the other a filament lamp.

In the laser system, the beam is passed through a beam expander to provide a uniform bundle of collimated light with a diameter sufficiently large to produce the smallest scanning spot desired.* The expanded beam is then

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* The spot size achieved at the focal surface is proportional to the ratio of the wavelength of the light source to the diameter of the beam (λ/D). Therefore, scanning spot size can be varied by changing the diameter of the beam entering the objective lens.

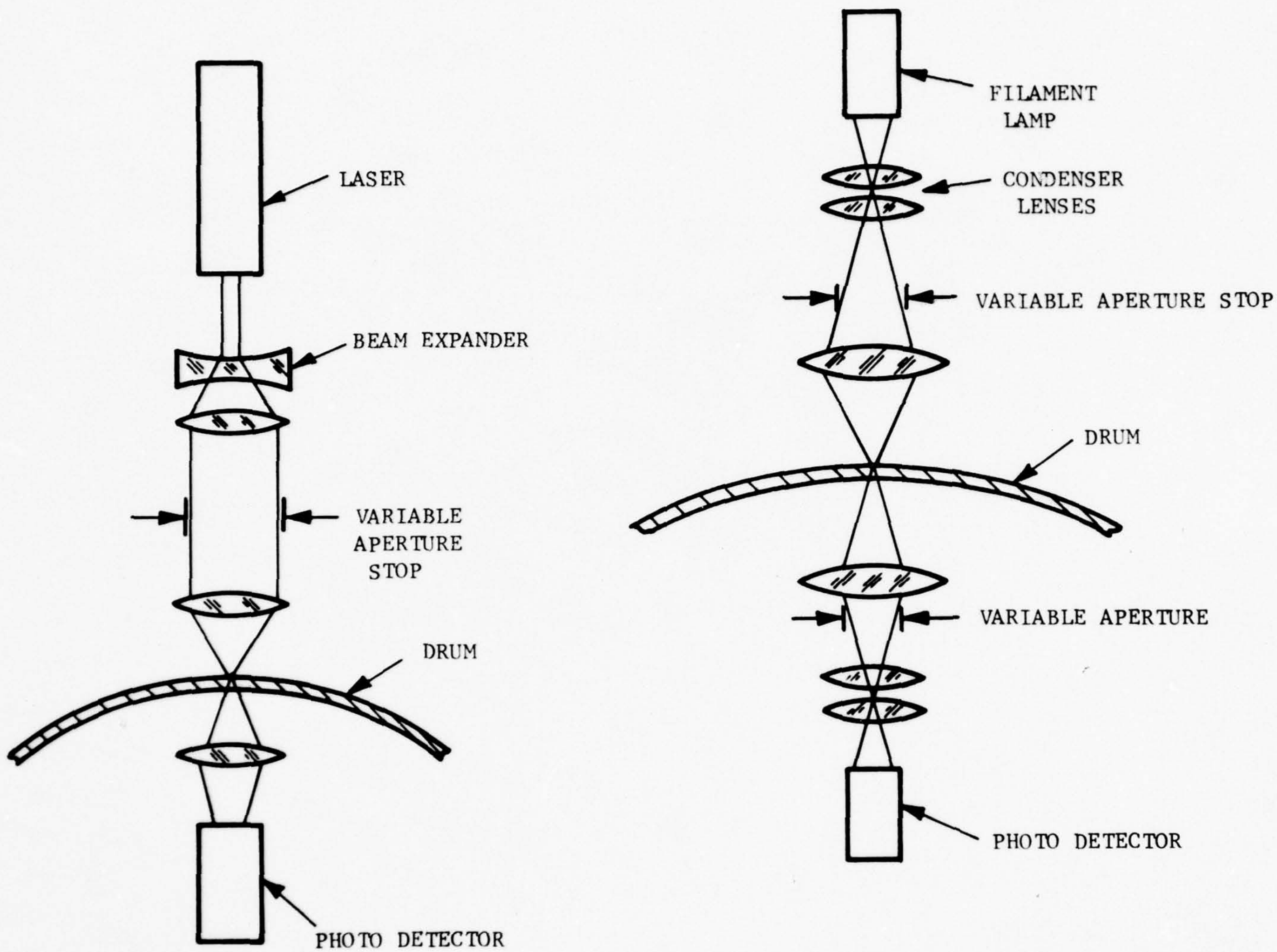

Figure 3-10. Alternative Approaches for Illuminating, Aperture Forming and Collection Optics

passed through a variable aperture stop and an objective lens that focuses it onto the film. Spot size is varied by changing the aperture stop. Smaller apertures produce larger spots and vice- versa. The collection optics can be relatively simple since operation is only on-axis. However, they must have sufficient numerical aperture to collect the entire cone of light transmitted. Since the variable aperture in the illumination path wastes energy at the smaller diameters, a laser of sufficient power must be used to maintain scanning rates at the lower operating resolutions.

In the filament lamp system illustrated in Figure 3-10, a regulated lamp supplies the light to illuminate a square aperture via an illuminating optical system that ensures equal illumination over the total spot area at the focal surface. Collection optics focus a pick-up (sampling) aperture inside the illuminated area on the film. Over-illumination is typically 20 percent to minimize the effects of scattered light entering the pick-up section.[11] A variable aperture stop is also used in the collection optics to vary the scanning resolution in this approach. Light transmitted through the sample is detected on a light-sensitive device such as a photomultiplier tube whose electrical current output is proportional to the light intensity input.

A reference beam, not shown in the figure, is also required to compare against the transmitted light in both of the optical approaches shown.

It should be noted that the variable collection aperture approach is also applicable to the laser system.

The drum scanner can provide high resolution scanning over large formats. Since there is no requirement to deflect the beam from the optical axis of its optical system, ultimate spot size is limited only by the wavelength of the source used and the quality of the optics used. Performance at 400 lp/mm has been achieved.* At the same time, the format is limited only by the

*LIPS Scanner: A laser scanning system built for Rome Air Development Center (RADC) by CBS Laboratories.

practical problem of mechanical accuracies in drum manufacture and motion control. Drum scanners handling film sheets of 40 x 60 inch have been build with recording spot sizes variable down to approximately 25 micrometers in diameter.*

Rotating drum systems are positionally accurate to within a few microns per centimeter. Apertures are usually limited to three or four square or circular sizes and, generally, the scan area may only be designated to within a few millimeters, so that "window" sizes can only be approximately selected.

The major limitation of this type system is the data rate that can be handled. This is a result of the speeds that can be obtained with rotating drums while trying to accurately control speed and dimensional stability. Systems capable of operating at a digitizing rate of 40,000 pixels/sec have been built and are in daily use.** The positional accuracy at this rate is ±1 micrometer/ mm of travel.

Also, drum scanners can handle only a single piece of film at a time, requiring a new setup for each picture to be scanned.

3.3.2.2 Translating Flatbed Scanners

Flat-bed systems are slower than rotating drum systems. They do, however, have the advantage that they can accommodate glass plate, roll film, and cut film, and can operate with ease at very small raster increments down to 1 micron or less because of the flat image plane and slow rates

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* Raster Finishing Plotter: A laser recorder also built by CBS Laboratories for RADC.

** Perkin-Elmer Line Scan Image Generator II (LSIG); rate limited by presently used A/D converter.

A flat bed scanner has a stationary optical system through which the image plane is moved on two orthogonal stages. The film is mounted on a precise flat glass platen in this plane. The stages are constructed using roller bearings or, for more accurate work, using high-stability granite and air bearings. In both cases, the stages are moved using stepping motor or high-speed servo motor-driven lead screws. Depending on the accuracy requirements, X and Y increments are measured by one of the following methods: a rotary encoder attached to the lead screw, a linear encoder attached to the stages or, for ultra-high accuracy, laser interferometers attached to the stages.

An optical schematic of a typical flatbed microdensitometer is shown in Figure 3-11. A stabilized illumination source underneath the stage is directed through fixed pre-slits. The use of apertures (slit and circular) in the illumination optics allows matching the area of the sample being illuminated to the scanning aperture, thus reducing stray light. An area illumination system (the fiber bundle in Figure 3-11) illuminates an area larger than the scanning aperture for viewing on the image plane and at the viewing screen. A variable-magnification image system is used in conjunction with fixed or adjustable pick-up slits to measure the light intensity at the image plane.

Matched illumination and scanning optics provide optimum illumination and measurement accuracy. The light-sensing unit is a specially selected high-gain, low-noise photomultiplier with an infrared filter in the optical system to prevent excessive thermionic emissions.

The microscope objectives are easily changed to provide a greater range of magnification. A telescope is provided to allow accurate matching of preslit and scanning aperture position.

Major advantages of flatbed systems are high positional accuracy (within a few micrometers over several inches), and excellent resolution (typically several hundred lines per millimeter). In general, a wide assortment of scanning aperture shapes and sizes are available. Digital image sizes may

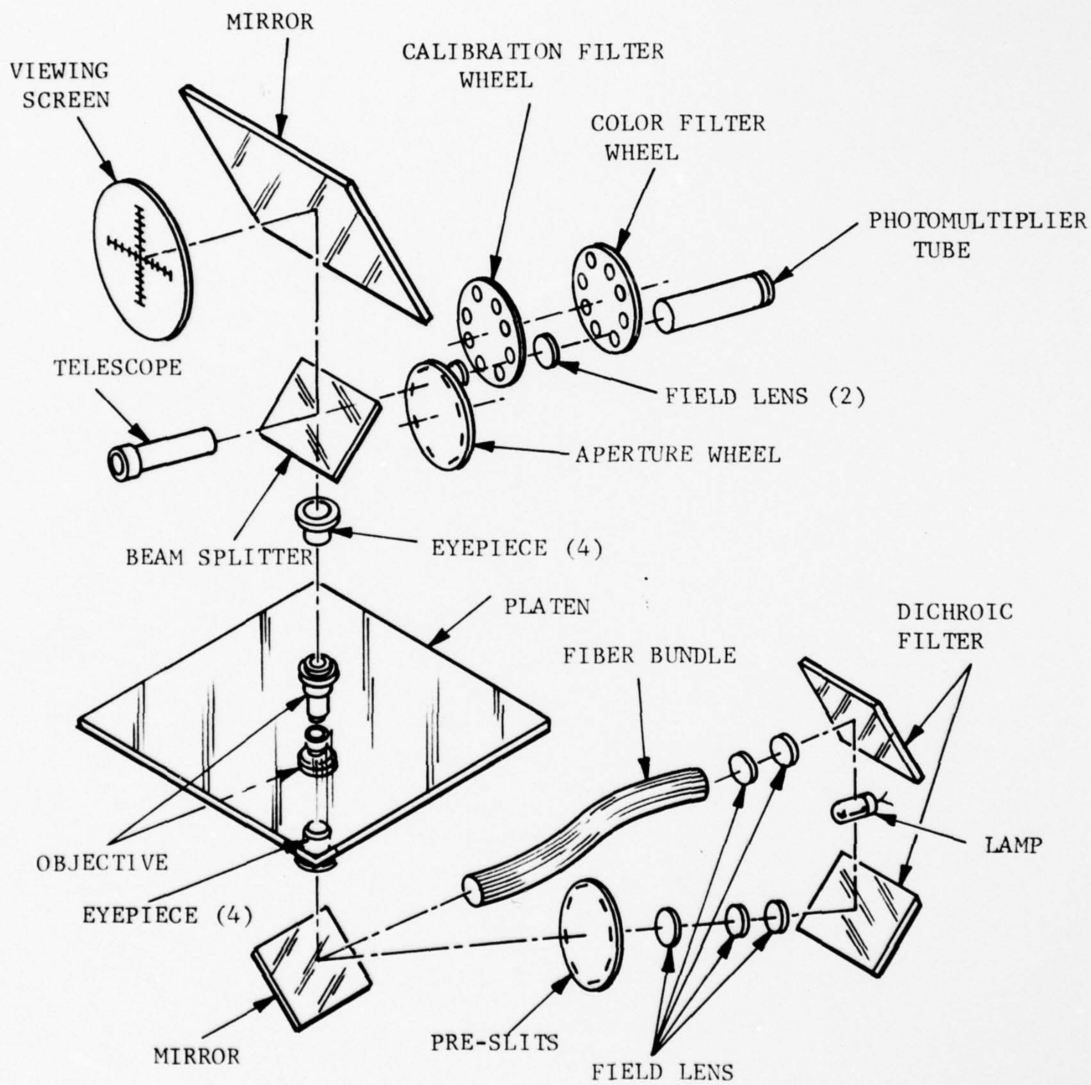

Figure 3-11. Optical Schematic of Perkin-Elmer PDS, Flatbed Microdensitomer. Model 1010A

be precisely selected and large sampling matrices (up to 200,000 pixels square) may generated.

The main drawback of these instruments is a limitation in the speed of digitization. A typical instrument can scan at rates up to 50 mm/sec. However, some granite-based instruments are capable of rates up to 200 mm/sec with an accuracy of approximately ±5 micrometers over several inches of travel.

Slow speed is an advantage, however, from the photometric point of view. The longer integration time available increases the density range of these instruments, typically from 0 to 4 density units or higher.

3.3.2.3 Rotating and Oscillating Mirror Scanners

Mirror systems utilize either a rotating, multifaceted mirror or an oscillating flat mirror to move a light beam across a film sample. The transmitted or reflected light is focused onto a photomultiplier and the current signal is amplified, sampled, and digitized. The light source may be either coherent or incoherent; however, for high-speed, high-resolution applications the coherent illumination from a laser source is usually preferred.

Mirror scanners can be separated by types into the following groups:

- Self-Resonant - Operate at a fixed frequency but can be varied in amplitude.
- Variable Frequency - Follow an analog input and can be controlled in both frequency and amplitude.
- Rotating Polygons - Scan through a fixed angle and because of high inertia, can be changed in frequency only at relatively slow rates.

3.3.2.3.1 Self-Resonant Scanners. Torsion rod and taut band devices constitute the self-resonant class. Both are excited electro-magnetically: the mechanically resonant rod by an armature in a varing magnetic field, and the spring (resonant taut band) by a moving permanent magnet armature. The

operating frequency in both cases is a function of the natural spring constant and the inertia of the moving elements, including the mirror.

The frequency range of the torsion rod devices is broad: 400 Hz is generally considered the practical low end and 22,000 Hz, the high end for good performance in commercial practice.[12] Mirrors to 2.5 cm in diameter can be used at the low scan frequencies, with the allowable size reduced for higher scan frequencies. Since the resolution* capabilities of mirror-type scanners are proportional to the aperture of the mirror, the higher frequency torsion rod scanners will have lower resolution capabilities than the slower ones for a given scan angle. Furthermore, the maximum scan angle that can be achieved with torsion rod devices generally reduces with higher operating frequencies, thereby further reducing the resolution capabilities of this type scanner operating at higher scan rates. The curves in Figure 3-12 indicate the resolution achievable as a function of mirror size and scan angle. Maximum scan angle achievable with torsion rods is approximately 15° and this is at the lower frequencies. These units scan symmetrically about their static center and while the scan frequency is fixed for a given unit, the amplitude, which governs the scan angle can be modulated. Also, it is relatively easy to synchronize a torsion rod unit with a second unit or with another type of scanner.

The taut band units overlap the low end of the torsion rod type's frequency range having an upper limit of about 1000 Hz. While they can be operated

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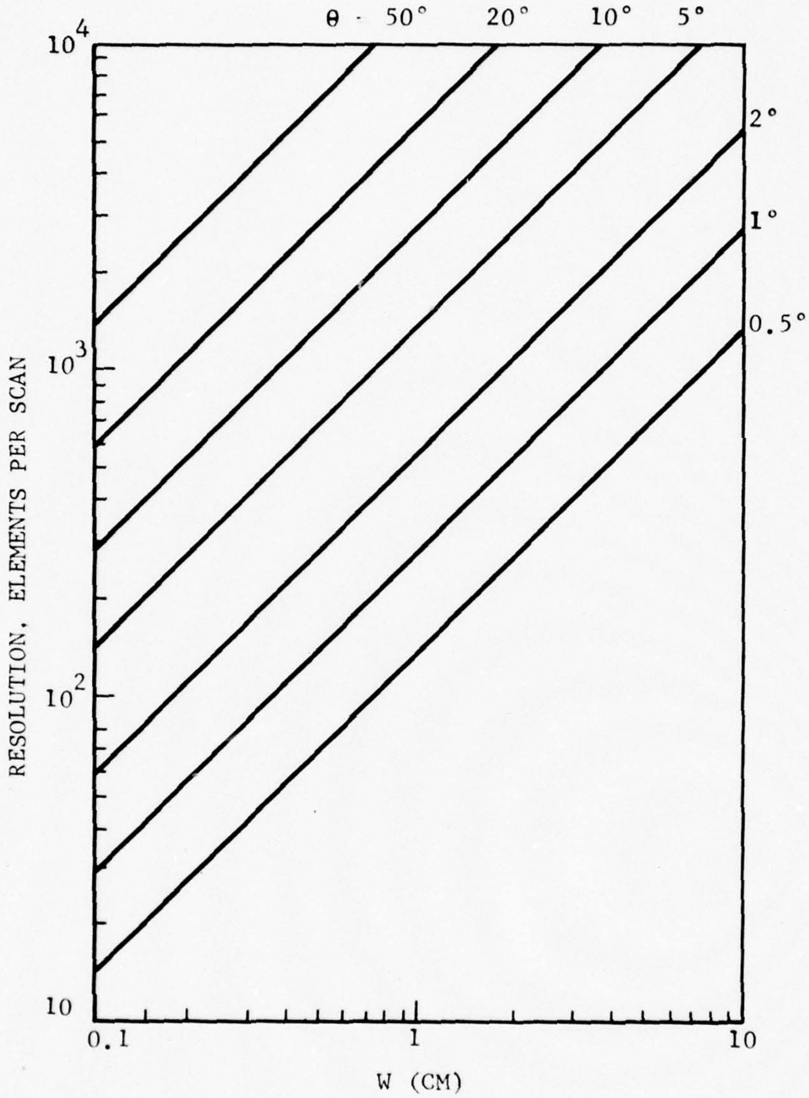
* In reference 13 Zook defines the resolution of mirror-type scanners as the maximum number (N) of resolvable spots available for deflection in one dimension (pixels per scan line). He expresses it in terms of the maximum deflection angle ϕ_m, the aperture of the mirror (W), the wavelength of light (λ), and e, which is a number that depends on the uniformity of illumination of the mirror and the criterion used for resolution, as follows:

$$N = \phi_m W/e\lambda$$



$N = \theta/\theta_d = W\theta/e\lambda.$

θ_d = Limiting angular spread due to diffraction

θ = Peak-to-peak deflection angle

e = Aperture shape factor = 1

λ = Wavelength of radiation = 633 NM

N = Number of resolution elements per scan

Figure 3-12. Number of Resolution elements N Versus Aperture Width W for Various Peak-To-Peak Deflection Angles.

down to 2 Hz; 5 Hz is usually the practical lower limit.[12] Mirrors to 10 cm square can be accommodated. Maximum scan angle is 30°. As with the torsion-rod type, taut-band devices scan symmetrically about their static center and can vary scan amplitude. Phase-locking is difficult and complex. Therefore, this type of device is seldom used in pairs. Their ability to move relatively large mirrors through large angles gives taut-band units a higher resolution potential than the torsion rod devices.

3.3.2.3.2 Variable Frequency Scanners. Devices in the "variable frequency" category include those with galvanometer movements and those using the piezoelectric phenomenon to obtain motion.

Galvanometers may be of the moving iron core or wound armature type, and may be supported in bearings or by a taut wire spring. In the moving iron type, a high-permeability magnetic material is rotated in a fixed magnetic field by an adjustable current. The armature is usually supported on a shaft mount in precision bearings. To improve bandwidth, electrical and mechanical damping is often incorporated. The wound armature devices, which cover the high-frequency end, usually are supported by a taut wire spring that also serves as the current conductor. Oil or magnetic damping is often used. Being analog devices, controllable both in frequency and position, they offer virtually unlimited operating modes, including holding a fixed position and scanning any sector either symmetrically about the center or over any selected portion of travel. Except when operated at their natural frequency, power requirements are orders of magnitude higher than the requirements of self-resonant types. Scan angle for the iron core devices can be as large as 30° and, for lower frequencies, mirrors up to 10 cm square have been mounted. Wound armature types generally are used for small excursions to 5°, and with mirrors a millimeter or less in diameter.[12] From curves presented by Zook in reference 13, the resolution versus scan frequency limits for galvanometer-type scanners are estimated to be approximately 10,000 pixels per scan at a scan rate of 100 scans per second and approximately 50 pixels per scan at approximately 25,000 scans per second.

Piezoelectric devices have been made in a variety of configurations. They are composed of two wafers of ceramic material, bounded into a biomorphic unit in a cantilever mount, with a mirror affixed so that its rotation axis coincides with the midpoint of the bending elements. The wafers are arranged so that when opposing electrical fields are applied the piezoelectric effect causes one to expand and the other to contract, bending the assembly and so moving the mirror. Motion is proportional to the voltage applied. High voltage is required, complicating drive and control circuits, but virtually no current is needed to hold the mirror in any fixed position. With a small mirror and short wafers, the frequency attainable can exceed 45,000 scans per second. Mirror scan angle usually is very small, minutes of arc, at high frequency and is limited to 2° maximum.[12]

3.3.2.3.3 <u>Rotating Mirror Scanners</u>. Rotating polygons (spinners) constitute the third class. They can be driven by any type of motor, including air turbines for high speeds. These units offer a great variety of scan capabilities and can be operated from very slow to extremely high scan rates and from scan angles approaching 180° to very, very small. Mirrors can be large. Scan frequency is the product of motor speed in revolutions per second and the number of facets. Maximum attainable frequency is restrained by structural considerations and by the point at which facets deform from stress induced by centrifugal force.

The spinner is the element that imparts scanning motion to the laser beam in a direction orthogonal to the spinner axis. Spinners can be pyramidal, prismatic, or polyhedral in format, and the reader is referred to references 14 and 15 for an in-depth understanding of the characteristics of the various spinner configurations and the rationales for their selection. They are all limited in speed by basic burst-pressure constraints. In reference 16, the maximum rotational speed allowed (with a safety factor of 4) for a beryllium spinner is shown to be:

$$w_m = \frac{355{,}000}{r} \text{ rad/sec}$$

where

r = radius from spin axis to facet surface, in millimeters.

The radius required is a function of desired f/no (beam relative aperture), number of facets (N), and the focal length of the lens (R) to be used. This relationship is also given in reference 16 as:

$$r = R/_{f}\ (2 \sin \pi/N)$$

Typically, the resolution and format requirements establish the minimum radius that can be used, and this minimum radius then dictates the maximum rotational speed possible, based upon the burst pressure formula.

To this point, the rotating and oscillating deflection devices themselves, without reference to a system, have been discussed. In considering their application to systems, both single-axis deflection and scanning in two orthogonal directions will be covered.

The system options for mechanical-type scanners can also be classified by what is moving relative to a fixed coordinate system: the focal point, the film, or both, If the film remains fixed while it is being scanned by a moving focal point, then a two-axis deflection system is required to scan through a "raster" on a "frame" basis. Motion of the film alone does not apply to mirror scanner systems; but, one of the two axes of area scan can be provided by moving the film and the other by deflecting the focal point. This is usually referrred to as a "line scan" approach.

3.3.2.3.4 Raster Scanners. Very often raster scanning on a frame basis is accomplished with two scanners. They may be paired units or units of dissimilar types. A rotating polygon often is combined with a galvanometer or resonant scanner for this application. Self-resonant, galvanometer, and piezoelectric types can be used in pairs or in combination with each other.

Torsion rod units are well suited for raster scanning because it is easy to phase-lock them, they require the simplest and lowest power driving circuit, and have a virtually unlimited operating life.

For small angles and very high frequencies, two piezoelectric units would be very suitable. Taut band units are difficult to lock in phase and are not generally used in dual scanner systems.

Because galvanometers and piezoelectric devices follow an input signal precisely, they do not require phase lock. Phase lock also can be avoided where a variable frequency device is used in conjunction with a fixed frequency device if the fixed frequency device is used as the master. For best results, whether using a pair of similar units or two different devices, the scanner operating at the higher frequency should be used as the master.

A torsion rod is also relatively easily controlled in a phase-locked system, but the rotating polygon imposes difficulties that require more sophisticated circuitry. Torsion rods tend to drift only slowly, principally with changes in thermal conditions; hence, control bandwidth can be small and gain high.

The rotating polygon, however, tends to hunt quite rapidly about the set frequency rather than drift. The bandwidth required, therefore, is relatively wide and the control circuit complex.

3.3.2.3.5 Line Scanners. Either oscillating or rotating mirrors can be used as line scanners in conjunction with either a precision film transport or a translating platen to provide the required motion along the second axis.

Rotating mirrors have been used as line scanners in a number of laser scanning systems. They offer a number of advantages for applications requiring line or raster scanning at a constant angular velocity, namely:

- High scan resolution
- High scan angular velocity
- Low light loss

- Low optical distortion
- Nearly constant scan angular velocity

These advantages generally offset the intrinsic disadvantages, which are:

- Extremely close tolerances are needed in fabrication, assembly, and balancing
- The line scans are not triggerable by external pulses
- The motor drive frequency must be extremely stable[17]

Problems sometimes encountered with rotary scanners are:

- Limited bearing life in high-speed operation
- Long dead periods between useful scans as the laser beam crosses over from one mirror face to the next
- Large moment of inertia, leading to long start-up time
- Generation of disturbing sound or vibration

Limited bearing life is a problem at rotational rates beyond 24,000 rpm for a rotary polygon directly driven on a motor shaft. The problem can be avoided with static or dynamic air bearings which can be free of rubbing or rolling contact.[18] Suitable air bearings can function at speeds up to a million rpm, but are expensive.

The delay between successive scan lines from a polygonal scanner can be avoided in various ways. If some waste of laser beam power is permitted, the beam diameter could be made quite a bit larger than a single polygon mirror facet. Two successive line scans will then appear simultaneously, with one starting a new line as the previous one is being completed.

Another option associated with mirror scanners of either the oscillating or rotating variety is the use of a flat field or curved field optical system.

Typical curved field and flat field systems are illustrated in Figure 3-13. The major difference between them are in the relative complexity of the optics and focal surface.

In the curved field system, a relatively simple objective lens, located in front of the mirror, focusses the collimated beam onto a curved focal surface. The mirror or multi-faceted spinner which is between the lens and the focal surface deflects the converging beam such that the locus of focal points is a circle. Hence, the film must be made to conform to this circular scan locus in order to maintain a uniform spot size and a linear scan (for a constant angular velocity of the spinner, information elements, or pixels, occupy equal angular increments in equal time) across the storage medium. This can be accomplished by forming moving film such that it conforms to the circular locus as it is transported past a scan gate by a capstan, or more conventionally, by providing a translating stage with a curved platen and vacuum system to hold the film in the required shape during a scan.

In the flat field system shown in Figure 3-13, the incoming collimated light from the beam expander is deflected by the spinner and, then, is focussed by the lens into a moving focal spot at the film plane. This flat field lens has a set of focussing elements and field flattening elements to provide the flat locus. In some designs, the entire space between the scanner and the focal plane is filled with optical elements; seven or eight elements are often needed to provide the desired correction over an adequately wide field. In contrast to the relatively simple 3-element lenses employed in curved field systems, considerable optical complexity is added to simplify the handling of the film. It does allow, however, the scanning of images on non-flexible base materials such as glass. Another advantage of the flat field over the curved field system is that it is not sensitive to axial translations of the spinner with regard to spot positioning errors. However, like the curved field systems, it is susceptible to angular differences in spinner facets that may be caused by manufacturing tolerances or wobble during operation.

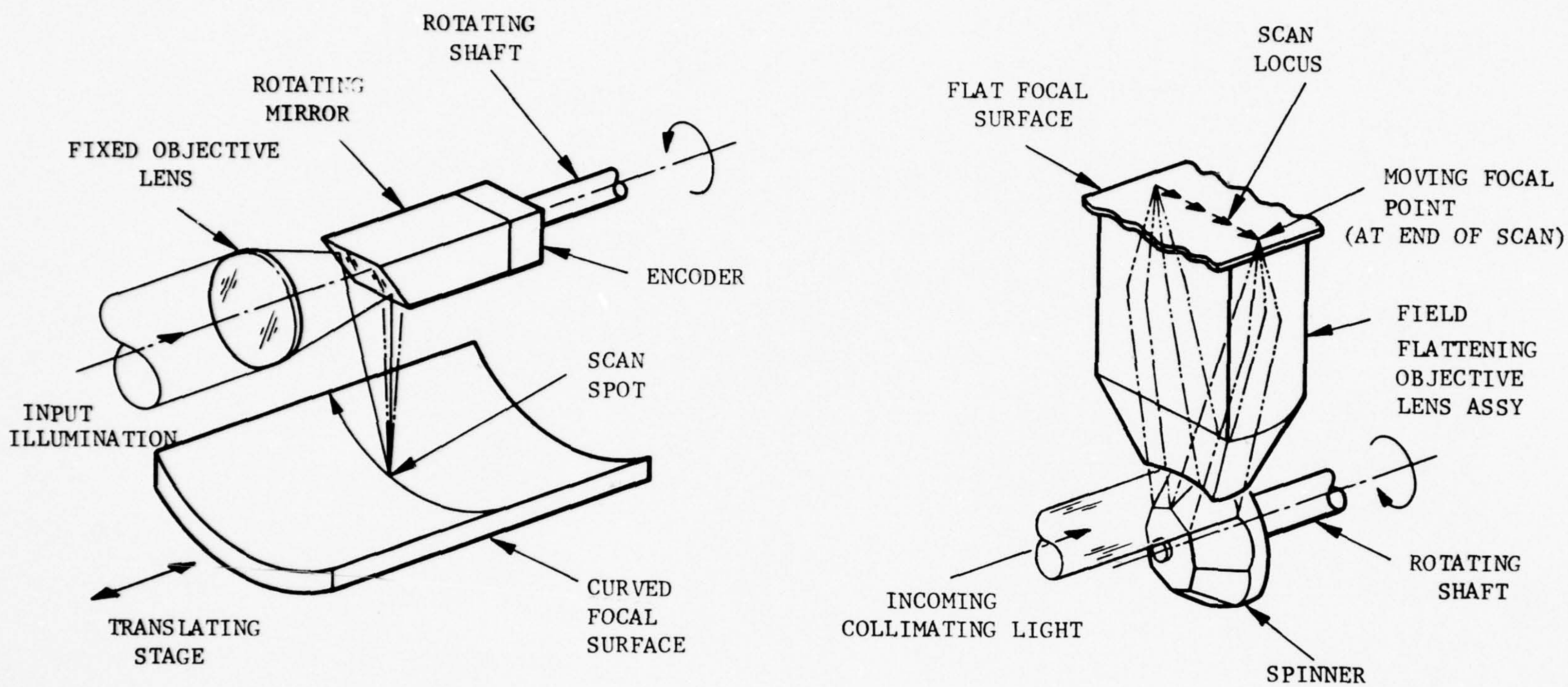


Figure 3-13. Typical Curved-Field and Flat-Field Scanning Systems

In addition to complex optical design, other disadvantage of the flat field approach include:

- Non-linear scan.
- Non-uniform spot profile.
- Spot aspect-ratio control involves critical movement of cylindrical lens or critical tolerances on aperture.
- A rotary encoder cannot be used directly attached to the spinner to give the position of the beam on the focal surface. A transfer function is required to compensate for the geometric distortion at the image plane introduced by the field flattening optics.

3.4 SOLID-STATE SCANNERS

The rapid development of arrays of discrete photodetector elements has brought about a variety of solid-state scanner systems. In these scanners, instead of mechanically or electronically scanning a single beam across the area of interest, the area is sampled in small, discrete adjacent areas by electronically switching between detectors in the array. Hence, arrays with a sufficient number of elements to cover the area of interest at the desired resolution allow scanning without any moving parts. Unfortunately, with the current state of technology in producing area arrays, this is only true for small areas at high resolution or larger areas at lower resolutions.

A solid-state image sensor consists of an integrated structure containing:

- An array of sensing elements in which incident light is absorbed and converted to electric charge.
- An array of storage elements in one-to-one correspondence with the sensors on which the integrated charge is stored.
- A scanning circuit for sequential readout of the stored charge.

Solid-state devices are available in two formats:

- Linear arrays containing up to 2048 detectors.
- Two-dimensional, or area, arrays comprised of matrices of up to 380 x 488 detectors.

The sensor and storage elements may be diffused photodiodes or surface-depletion layers induced by a voltage applied to semi-transparent electrodes of a material such as polycrystalline silicon. The readout mechanism may be a digital shift register which controls a set of multiplex switches to sequentially empty the charge on the individual sensors onto a common output line, or it may be an analog shift register of the CCD or bucket brigade type. In the latter case, the sensors are emptied simultaneously into corresponding stages of the analog shift register and are then shifted sequentially to the output node. The basic building blocks can be combined in several ways to produce the various

types of solid-state image sensors. Self-scanned photodiodes (SSPD), charge-coupled devices (CCD), charge-injection devices (CID), and charge-coupled photodiodes (CCPD) will be discussed briefly.

3.4.1 Self-Scanned Photodiode Arrays

The classical SSPD array utilizes photodiode sensors and digital shift register scanning. Its major advantages stem from the properties of the sensors, i.e., repeatability, high quantum efficiency, broad spectral response, and low dark current.[19] Since the sensing area is covered with only a single layer of silicon dioxide, reflection losses are minimized; since the layer can be made several micrometers thick, interference effects are minimized; and since it is completely transparent, there are no absorption losses. A final advantage of photodiodes is the ease with which they are fabricated in different shapes and sizes.

The digital shift register scanning used in a SSPD also has some advantages. First, since it is used only as a multiplexer, the clocks are much less critical than in a CCD. This, combined with the lower clock line capacitance, makes it easier to fabricate adequate drive circuits. A second advantage stems from the fact that the diodes are multiplexed directly into the output. This minimizes crosstalk and blooming and eliminates the possibilities of image smearing due to transfer inefficiency effects.

The two major disadvantages of the SSPD structure are:

- There are fixed patterns in the dark level due to slight variations in switch characteristics. These fixed patterns typically amount to about 1 percent of the saturated signal level, and in those applications requiring more than 100:1 dynamic range it is necessary to correct for the fixed pattern on an element-by-element basis.
- The thermodynamic noise associated with detecting charge on the output capacitance is high. The lowest readout noise that has been reported for long SSPD arrays is in the range of 500 electrons compared to less than 100 electrons for CCD arrays.[19]

3.4.2 Charge-Coupled Detector Arrays

The conventional CCD sensor array utilizes field-induced surface depletion layers as detectors and a CCD analog shift register for readout.

The charge, created by photo interaction, is stored in a potential well formed by modulating the voltages applied to a series of electrodes associated with the detectors. After the charge has been allowed to accumulate, it is collected by increasing the voltage on selected electrodes to create a deeper potential well under that electrode. If the electrodes are sufficiently close together, the charge will spill over into the new well, effecting a shift. Thus, by properly modulating three voltages, an optically generated charge can be collected and thus swept out as if it were stored in a shift register.

Linear imaging arrays can be designed in three ways:

- A simple CCD shift register can be used if it is clocked in such a way that the shift-out time is much less than the integration time. This condition reduces image smear caused by shifting pixels through light-sensitive regions.
- Separate image sensors and a shielded readout register are used. After integration in the sensors, the charges at each of the sensors are transferred into the shift register in parallel. The line of video is then shifted out serially via the shift register while a new line is being integrated.
- A line of sensors and two shielded readout registers are used. After integration, odd-numbered pixels are transferred into one readout register, and even-numbered pixels are transfered into the other readout register. The information in the two vertical registers is clocked into a two-bit horizontal register, thus reforming the pixels in the order in which they were formed. This design doubles the effective data rate at which the device may be operated.

There are two types of area arrays, TDI (time delay integration) and integrating arrays. The TDI arrays have the ability to simultaneously integrate and

shift an array of charge packets at a precisely controlled average speed. The average speed is governed by the frequency of the crystal-controlled oscillators driving digital circuitry. Area arrays which stare at a scene, integrating for a period of time to form a frame of video information, are called integrating arrays or framing arrays. The choice of one or the other of these arrays is application-dependent.

Charge-coupled devices have most of the advantages of silicon vidicons but do not suffer from parabolic distortion, as the electronic sensors do, and have zero lag.

Compared with SSPD's, the major advantages of a CCD imager are the low fixed patterns and low readout noise. They can also operate at high rates, but, though adequate for most applications, do not have as large a dynamic range. Also, they have very little response in the blue region of the spectrum and none in the UV. Hence, the photodiodes are a better choice if color images are to be processed.

An important feature of CCD's for solid-state imaging is that the signal charge is delivered to a low-capacitance node. The voltage at this low capacitance node is large, and a good signal-to-noise ratio is obtained. The noise associated with these devices is primarily due to the reset noise associated with charging the node capacitance and thermal noise of the output amplifier. The noise can be reduced to an even lower level using various signal processing techniques, of which correlated double sampling is most common.[20]

3.4.3 Charge Injection Devices

The CID utilizes field-induced surface-depletion layers as detectors and digital shift registers for scanning. Therefore, the essential difference between the CCD and the CID is the method of charge readout. In contrast to CCD's, in which the signal charge is transferred from the storage resister sequentially to a readout amplifier at the edge of the array, the CID readout takes place right at the image site by transferring charge from under one electrode to another at each imaging site.

The excellent antiblooming properties of the CID follow directly from the chip architecture, where each imaging site is surrounded by a field-stop diffusion or a region of thick oxide. In either case, overflow of charge along the surface is prevented and because the CID is usually fabricated on expitaxial material, charge diffusion away from a well which is overfilled is greatly attenuated. This architecture provides an antiblooming capability in both row and column directions.[20]

The x-y addressing capability of the CID provides the possibility of non-sequential scan readout. For example, if a decoder similar to those used on an MOS random access memory were provided, then a completely random read-out could be obtained. In addition, the signal charge in the CID may be read out non-destructively.

Finally, the CID architecture provides nearly complete utilization of the device area for active imaging sites. Up to 90 percent of the chip area can be used for active imaging sites in the CID, in contrast to the frame transfer and the interline transfer CCD's, where less than half the chip area is used for imaging. Moreover, if these imaging sites are covered with a transparent electrode, nearly the theoretical silicon quantum efficiency can be achieved on a front-side-illuminated device.

3.4.4 Charge-Coupled Photodiode Arrays

The charge coupled photodiode array uses photodiodes as sensors and CCD analog shift registers for readout. The sensing region is a row of diffused photo-diodes on 16-micrometer centers which operate in the integration mode. At the end of each integration period, the charge on the diodes is simul-taneously dumped into one of two CCD registers for readout. The output from the even register is delayed one-half sample period with respect to the odd register so that a full wave signal is obtained simply by multiplexing the two outputs off-chip. Except for a 16-micrometer aperture over the row of sensing diodes, the entire chip is covered by aluminum metallization to prevent spurious response.[19]

This new device structure (CCPD) combines the advantages of CCD readout with most of the advantages inherent in SSPD technology.

Some examples of the SSPD, CCD, CID and CCPD arrays that are currently available and their pertinent characteristics are presented in Table 3-1.

3.4.5 Scan Implementation Alternatives

All of the solid-state area arrays previously mentioned can be used in an all-solid-state area scanner requiring no moving parts. However, as indicated in Table 3-1, the arrays currently available do not contain a sufficient number of detectors to scan large formats at high resolution. But, their compact size and low power requirements make them ideal for use in a hybrid scanner that utilizes two mechanical translating stages to position the solid-state area scanner anywhere in the format. (See Figure 3-4.)

All of the linear arrays discussed also require a hybrid approach for area scanning, wherein solid-state techniques are used to scan along the linear array and a single translating stage is used to move the array or the film at a uniform rate along the other axis. A sketch depicting this solid-state/mechanical scanning concept is shown in Figure 3-14.

Relay optics are required to transfer the image from the film plane at the desired resolution (sample size) to the available photodetector sites. Condensing optics may or may not be required, depending on the type of light source used and the practicality of imaging it directly on the film.

Since linear solid-state photodetector arrays available today contain no more than 2000 detectors each, for many applications several arrays must be butted together to provide the required number of pixels per line. Because of the physical structure of an individual array (typically twice as long as the actual photosensitive area), multiple arrays cannot be placed close enough together to maintain the pixel spacing inherent in the individual arrays. Figure 3-15 depicts two different optical butting approaches that have been used to produce linear scans comprised of more elements than are available in

TABLE 3-1

EXAMPLES OF CURRENTLY AVAILABLE SOLID-STATE ARRAYS

Array Type	No. of Elements	Element Size (μM)	Center-to-Center Dist. (μM)	Saturation Level (Electrons)	Responsivity ($e/\mu J/M^2$)	Response Non-Uniformity (%)	Dynamic Range	RMS Noise (Electrons)	Maximum Scan Rate (MHZ)
• Linear Arrays									
CCD 131 (Fairchild)	1024x1	13x13	13	$6x10^5$	200	±6	2500:1	240	20
CCD 121 (Fairchild)	1728x1	13x17	13	$6x10^5$	200		2200:1	270	2
RL 1728 B (Reticons SSPD)	1728x1	15x16	15	$2x10^7$	760	±15	10,000:1	2000	3
CCPD 1728 (Reticon)	1728x1	16x16	16	$6x10^5$	200	±7	2500:1	240	5
• Area Arrays									
CCD (Fairchild)	380x488	14x18	H-30 V-18	$2x10^5$	140	±10	460:1	434	5
CID (General Electric)	188x244	35x61	M-35 V-61	$2.4x10^6$	597	±7	1180:1	2000	5

Definitions:

- Saturation Level - Output Signal for minimum exposure to cause saturation.
- Responsivity - Output signal per unit of exposure (5000°K, 0.4 to 1.1 μM)
- Dynamic Range - Saturation level divided by noise equivalent exposure (NEE)
- Noise (NEE) - Peak-to-Peak noise divided by 5
- Response Non-Uniformity - Difference in response levels between most sensitive and least sensitive pixel, expressed as % of saturation level.

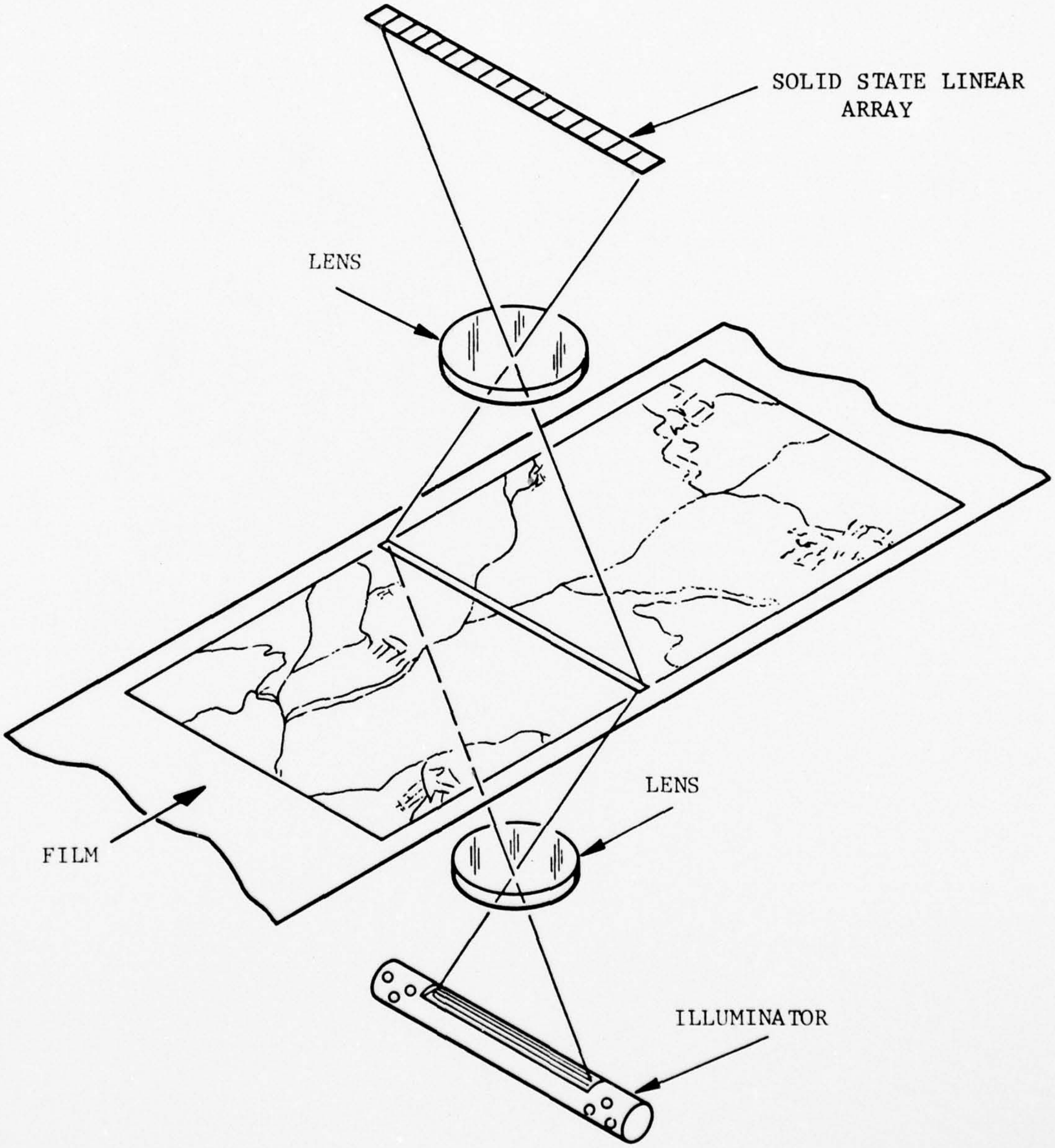


Figure 3-14. A Hybrid Scanner Concept Employing Solid State Line Scanning and Mechanical Motion for Area Scan

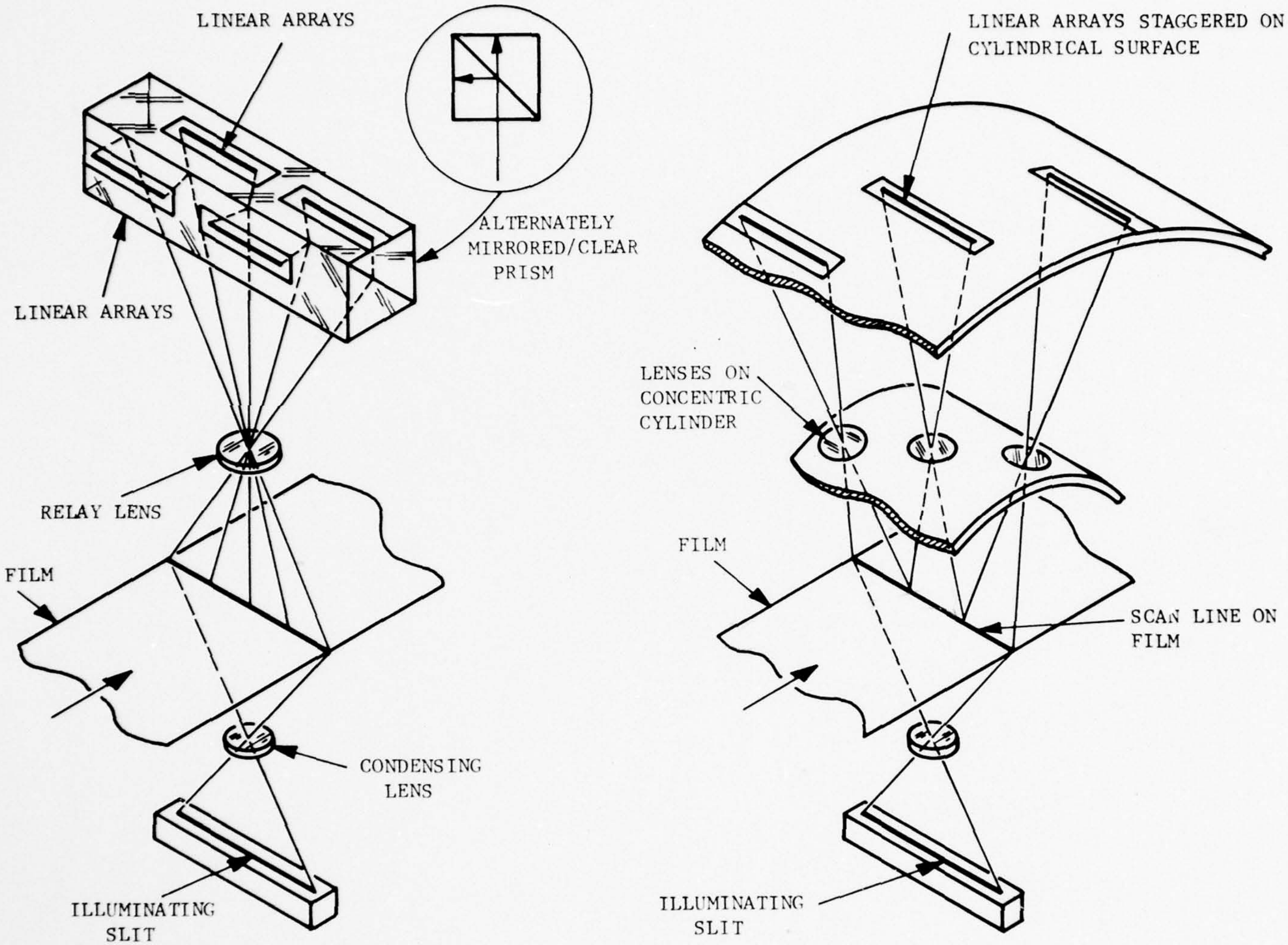


Figure 3-15. Two Optical Approaches for Butting Linear Arrays

a single commercially available array. The basic differences between the two approaches shown are in the focal plane assemblies and the imaging optics.

In one approach, the illuminated line at the film plane is imaged by a single lens onto the diagonal of an optical prism which is alternately silvered and clear so as to appropriately image a different segment of the line onto each of several detector arrays. The detector arrays are located alternately on the top horizontal surface and a vertical surface of the prism to receive the rays passed by the clear areas and folded by the silvered areas of the diagonal, respectively.

In the second approach, each segment of the illuminated line is imaged by a separate lens onto its associated detector array. Essentially, this approach involves a group of cameras that are mounted on a cylindrical surface to provide the required mechanical spacing of arrays, and such that the projections of all their arrays forms a straight line with uniform pixel spacing at the film plane. The optics associated with this approach are relatively inexpensive because relay lenses need only accommodate very narrow field angles and no additional optics are required between the lenses and the arrays. The mechanics associated with array alignment are no more complex than with other optical butting schemes; however, with a fixed focal surface configuration the resolution achievable at the film plane cannot be varied by optical-mechanical means without causing pixel overlaps or voids at the interface between adjacent arrays. This is not the case with the first approach.

Another way to increase the number of detector elements in a line scan is through electronic butting. In this approach, the focal plane assembly would be fabricated as shown in Figure 3-16 by staggering alternate arrays. The effective butting is realized by appropriately delaying output of one set of the alternate arrays. In the example depicted in the figure, the distance (D) between centerlines of alternate arrays is equal to the center-to-center distance between three adjacent pixels. Therefore, the detectors in the line of arrays designated number 1 will be sampling their third set of pixels when the detectors in line number 2 are sensing the set that lie in the same line

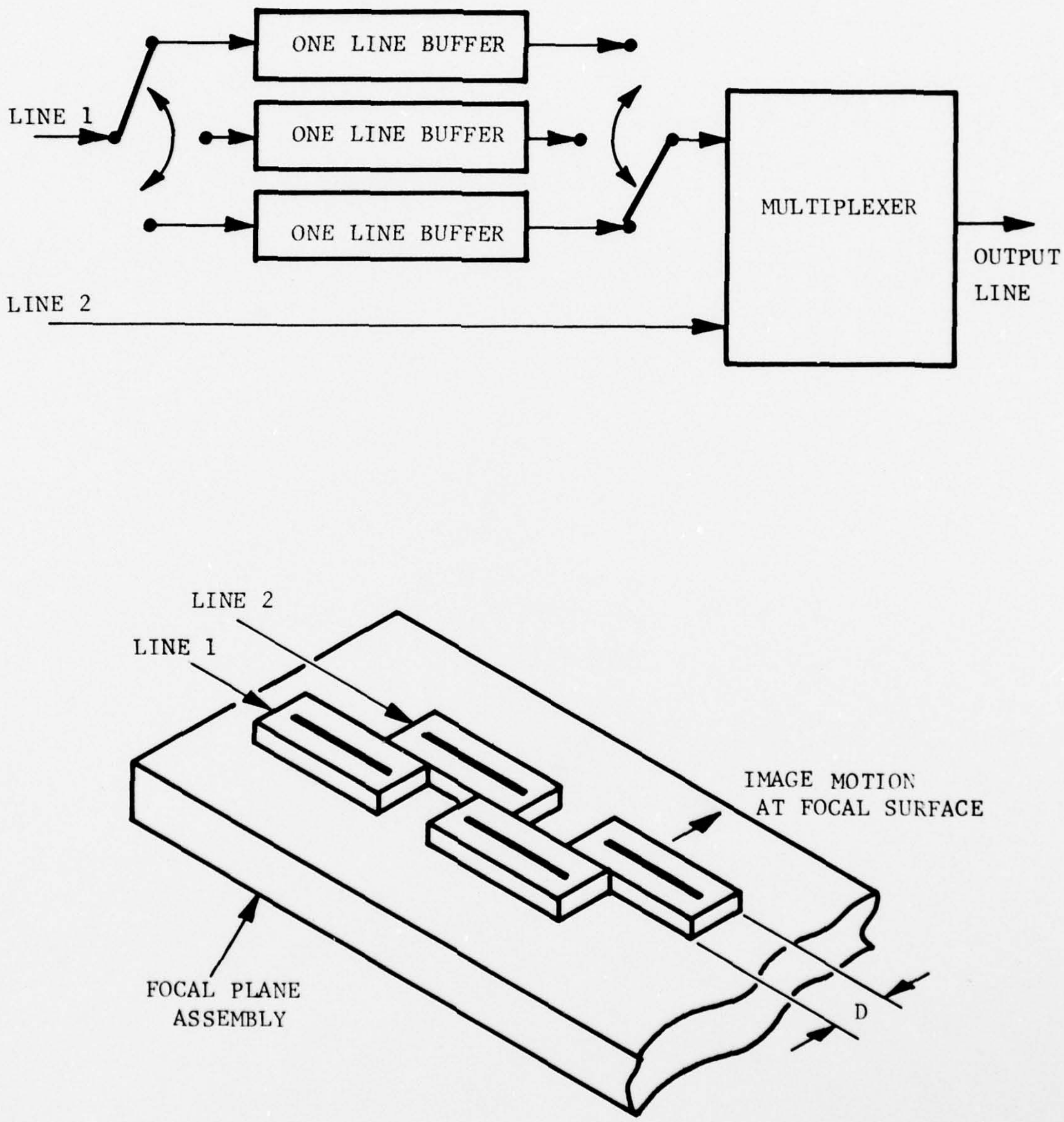


Figure 3-16. Electronic Butting of Staggered Arrays

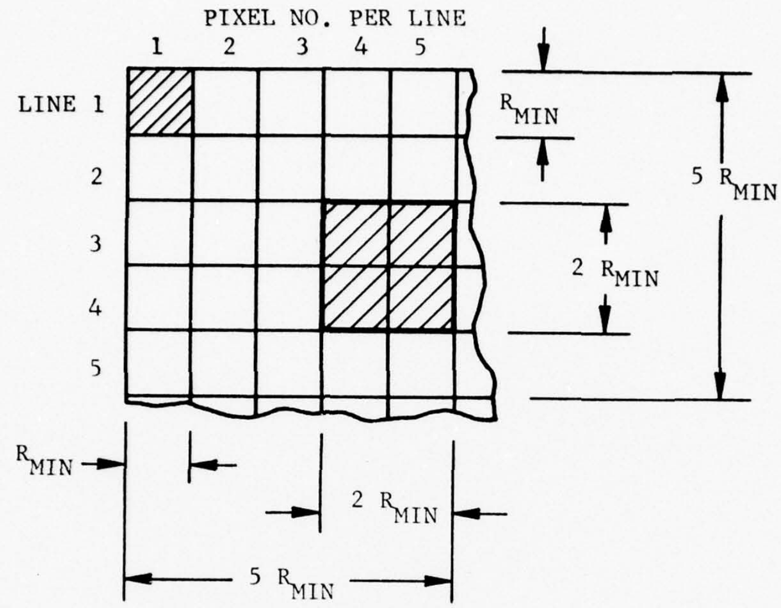
first sampled by number 1. By switching the output of the line 1 detectors sequentially through a set of three line buffers, and appropriately phasing the readout of these buffers to coincide with the output of the detectors in line 2, the two lines of data can be multiplexed into a continuous line, thus accomplishing butting of the arrays by electronic means.

In reality, this is not a viable approach, except possibly for some very special conditions. For typical commercially available linear arrays, the smallest the distance D could be is approximately 15 mm. With typical pixel dimensions on the order of 12 to 15 micrometers, it would be necessary to store more than 1000 lines of data to create the continuous line.

With all of the above-mentioned solid-state scanners, the easiest way to vary resolution is by electronic or digital processing means. As shown in Figure 3-17, resolution can be varied from the maximum resolution (minimum spot size) by whole number factors with microprocessors and a set of algorithms that combine detector outputs according to the appropriate rules for the desired resolution. Fractional changes can be realized by combining electronic combination techniques with optical reduction.

In summary, the major advantages of solid-state scanner technology, including self-scanned photodiodes, CCD's, CID's, and CCPD's are:

- The precise dimensions between pixels (geometric accuracy).
- The number of elements per line is limited only by the space available.
- All elements can be exposed in parallel and the effective data rate can be extremely high. Line scanners have been built with scanning speeds to 100 MHz, which is equivalent to 200M pixels per second.
- The detectors, readout circuits and amplifier are all on one chip.
- The feature of separate addressability permits select area (window) scanning by electronic switching in addition to the high data rates.
- Scanning of the detectors by solid-state techniques elliminates the need for moving parts, at least for one axis.



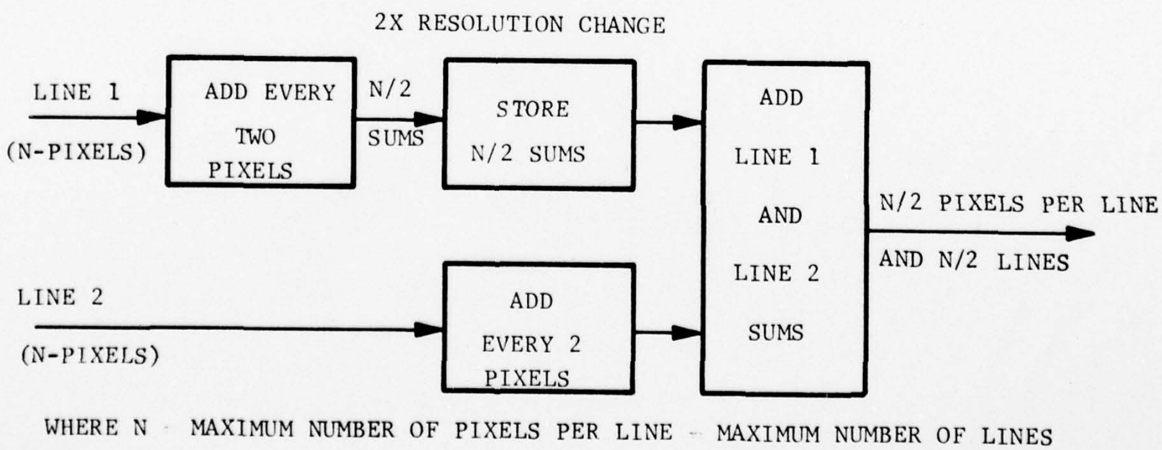


Figure 3-17. Variable Resolution By Pixel Combination Techniques

- Low voltage operation with high quantum efficiency.

The major disadvantage or problem is the fact that not all detector elements will be matched in responsivity; therefore, some method of calibration throughout their operating range must be provided. Also, the level of cross-talk between adjacent and neighboring pixels varies as a function of wavelength. Tests on CCD arrays at Perkin-Elmer indicate that there is considerably less cross-talk between pixels in the visible portion of the spectrum than there is in the near-infrared. Consequently, for applications in a film scanner it is better to avoid operations at the longer wavelengths, if possible.

SECTION 4

TECHNOLOGY CAPABILITIES VERSUS SCANNER REQUIREMENTS

4.1 GENERAL

Format accommodation, resolution, data rates, geometric accuracy, radiometric accuracy and dynamic range were identified in Section 2 of this report as the major performance criteria against which evaluation of different implementation technologies should be based. Various scanner technologies were discussed in Section 3. In this section of the report, the capabilities of each technology will be summarized and compared with the requirements set forth in Section 2 and Table 4-1. The format accommodation and resolution capabilities of the different technologies are summarized in Table 4-2; the geometric accuracy, radiometric accuracy and data rate capabilities, in Table 4-3.

4.2 FORMAT ACCOMMODATIONS AND RESOLUTION

A major influence upon scanning system design is the need for format flexibility, both dimensionally and in resolution. Dimensionally, it is desirable to attain a full frame size of 230 x 230 mm and be additionally adaptable to perform a sub-raster or "window" mode over a substantial number of picture elements (pixels) in both directions. In resolution variability, it should allow adjustment of the scan spot size (the footprint) on the storage material over a 5:1 range of spot diameter. Another major influence upon the scanning system selection is the need for relatively high resolution in terms of total number of elements per scan format. Interpreting this resolution from the point of view of the input data, the 20 to 100 cycles/mm input resolution range represents a full format resolution requirement between 4,600 to 23,000 image cycles per scan.

TABLE 4-1

SUMMARY OF SCANNER REQUIREMENTS

Format Accommodation	
Full format mode	Variable, up to 230 x 230 mm
Window mode	Variable, up to 2000 x 2000 pixels
Resolution	
	Variable, from 20 to 100 ℓp/mm in both modes
Scanning spot size	Variable, from 5 to 25 μm
Pixels per line (full format)	46,000 = 100 ℓp/mm 9,200 = 20 ℓp/mm
Lines per raster (full format)	No less than 9,200 to 46,000, as function of input resolution
Data Rates	
	At least 0.75 million pixels/sec, goal, 3.7×10^7 pixels/sec
Geometric Accuracy	0.001 to 0.002 percent
Dynamic Range	
	At least 200:1 (0.2 - 2.5 density units) (63.1 - 0.316% transmission)
Radiometric Accuracy	
6-bit quantization (min) 8-bit desirable	1 unit in 64 = ±0.035D or ±0.98%T 1 unit in 256 = ±0.009D or ±0.25%T

TABLE 4-2

FORMAT ACCOMMODATION AND RESOLUTION CAPABILITIES OF DIFFERENT TECHNOLOGIES

Technology	Maximum Pixels/ Line	Maximum Window Scan At 100 ℓp/mm	Approximate Resolution At Full Format With Single Unit (ℓp/mm)	Units or Segments Req'd. For Full Format Line Scan At 100 ℓp/mm	Comments
Electronic					
CRT	4000	20 x 20 mm	9	12	Adequate for window scanning applications in conjunction with precision translating stages. However, data rates at high resolutions are low.
Vidicon	2000	10mm x 10mm	4	23	
Image Dissector	4000	20mm x 20mm	9	12	
Electro-Optical					
Rotating Drum	Unlimited	Unlimited	400	1	Window and full format capability Inefficient in window mode Rates relatively slow Window positioning inaccurate
Translating Flat Bed	Unlimited	Unlimited	600	1	Window and full format Rates very slow
Oscillating Mirror	2000-10,000 (varies with mirror size and scan rate)	10mm x 10mm (2000x2000)	22 (10,000 pixels)	5	Window mode with translating stages Full format at low resolution and poor linearity
Rotating Mirrors	55,000	275mm x 275mm	120	1	Window and full format Inefficient in window mode
Solid State					
Linear Arrays	2000	10mm x 10mm	4	23 (4 in 1980)	Window and full format at high data rates and with accurate positioning
Area Arrays		(500 x 500) 2.5mm x 2.5mm			Larger arrays expected by 1980 will satisfy window requirements

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TABLE 4-3

GEOMETRIC ACCURACY, RADIOMETRIC ACCURACY AND DATA RATE CAPABILITIES OF DIFFERENT TECHNOLOGIES

Technology	Geometric Accuracy	Photometric Accuracy	Data Rates (Pixels/Sec)	Comments
Electronic				
CRT	0.05%	0.02 D	5×10^6	With distortion correction 4000-5000 pixels/line, max.
Vidicon	0.2%	0.02 D	8×10^6	With shading correction module
Dissector	1-2%	0.02 D	1×10^5	Non-constant spiral distortion.
Electro-Optical				
Rotating Drum	.002%	<0.01 D	1.5×10^5	
Flat Bed	.002%	<0.01 D	4×10^4	
Oscillating Mirror	.01%	<0.01 D	1×10^6	With reference grating limited to 10,000 pixels/scan
Rotating Mirror	.002%	<0.01 D	1×10^8	
Solid State				
Linear Arrays	.002%	<0.01 D	9.2×10^8	Several optically butted arrays in parallel
Area Arrays	0.1 μm	<0.01 D	5×10^6	Over single array

Since valid digitizing may be executed with no less than 2 samples per information cycle, this raises the pixel count to between 9,200 and 46,000 per scan, depending upon the resolution of the input.

The modulation at a given spatial frequency can be determined if the minimum spot size achievable with a diffraction-limited system is known. If the diameter, d, of the scanning spot is chosen to be the diameter of the first minimum of the Airy disk ($d = 2.4\lambda$ (f/No)), and the pitch of two successive spots, ΔS, is 1/2K, where K is the desired spatial frequency, then 100 percent modulation would be achieved at k ℓp/mm if d is also equal to 1/2K. As d increases with respect to 1/2K, the modulation decreases to a-b/a+b, where a equals the peak signal amplitude, and b equals the amplitude at the cross-over point between pixels. Thus, for d = 5mm, k = 100 ℓp/mm at 100 percent modulation.

A practical approach in systems having signal-to-noise ratios of 40 db or better, and with suitable power margins, is to work at the 50 percent power point on the Airy disk. (Typically, lasers have power to spare.) At this point, the spot diameter produced with the same optics would be 2.5 μm, and thus one can achieve scanning at 200 ℓp/mm at the expense of throwing away dynamic range, modulation, and power. A system designed to produce a spot of 5mm at the 50 percent point on the Airy disk would have a MTF of 50 percent at 100 ℓp/mm.

It is further known that the 2:1 sampling criterion is adequate only when the relative phase of the sampling interval is controlled with respect to the cyclic information (see Appendix A). If the sampling occurs precisely at the peaks and at the troughs of the image cycles, then 2 samples per image cycle are adequate. If, however, the peaks and troughs of the image fields bear no maximally phased relationship with the sampling intervals, then all sampling conducted at times other than at the precise maximum and minimum points will be reduced in detected intensity, and will be nulled to zero when occurring at the midpoints between the peaks and the troughs. To guard against this real condition during periodic sampling of an arbitrary field, over-sampling (beyond the Nyquist criterion) is sometimes instituted.

The use of over-sampling imposes an extra demand upon the digital image processing techniques in terms of the volume of the data that must be handled. If modulation transfer losses (derived in Appendix A) attributed to the information phasing problem can be tolerated, the system designer would favor sampling at the Nyquist limit. With that in mind, the format and resolution requirements are as summarized in Table 4-1.

Having addressed the resolution and manipulative requirements of the scanning system, the candidate techniques may now be evaluated in light of this understanding.

4.2.1 Electron-Beam Versus Laser Beam Versus Solid-State Devices

Electron-beam devices include the cathode ray tube (CRT) and the wide assortment of image sensors which include the vidicon family and the image dissector. Laser beam scanners are usually independent of the laser itself; the laser acts as a highly controlled light source whose output is scanned by acousto-optic or mechanical techniques. Solid-state devices include linear and area arrays of detectors contained, with their scanning and readout electronics, on a single chip.

Electron beams are remarkably submissive to positional and intensity control, as represented by the relative ease of deflecting moving electric charges. In contrast, the laser beam starts in a highly ordered manner -- coherent -- and requires effort to establish rapid and accurate control during information sampling. Since the photon of the laser beam conveys no net electric charge, its path is not directly controllable (as is the electron) by electric or magnetic fields. The solid-state devices, somewhat like the electron beam devices, are low-inertia devices that are scanned by electronic means. However, they do not require beam deflection. All pixels in a complete line are scanned simultaneously by electronically activating all of the prepositioned (fixed) photosites of the array. Various readout techniques are employed, as described in Section 3.

Electron beams are capable of rapid random access, while providing moderate resolution (in the context of these requirements). Laser beam random scan technology, although approaching the resolution of the electron beam, is not yet competitive in access speed, demonstrating the great advantage of the direct control of moving charges of the electron beam.

However, laser beams can be recurrently or periodically scanned to resolutions and speed far exceeding the capabilities of electron beam systems. This is due mainly to the ability to impart great rigor to a mechanical system which positions the focused beam of light with respect to the information-bearing medium.

Thus, if random access is a major requirement, then the electron beam addressed systems would hold an advantage. Similarly, if total format resolution is a driving requirement, then the laser system offers a clear advantage.

In the case at hand, we encounter a merging of both requirements: the desire for both random access of selected windows and the highly controlled accuracy and resolution within that window as well as over the full format. Not only is current electron beam and low-inertia laser beam technology not prepared to satisfy these needs simultaneously, but certain systems within each class will drop out because of sheer awkwardness of implementation.

For example, in the electron-beam class, the vidicon is not capable of more than 2000 elements of resolution per scan (2-inch vidicon).* Thus, a single sensor of this type will require 5 adjacent sub-raster scans to montage a full field of view of 9,200 elements and achieve 20 ℓp/mm resolution, or 23 to achieve 100 ℓp/mm. This is unwieldy because of the size of the tubes, and edge matching is extremely difficult because of the geometric distortion associated with electronic beam deflection as well as radiometric variability of tubes. Less strips can be employed to the extent that resolution is sacrified to the value of 2000 elements (maximum) per scan for a single 2-inch vidicon at a slow-scan rate.

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*The experimental 4.5-inch Return Beam Vidicon described in Section 3 is an exception.

This general limitation exists for the flexibly scanned laser system, such as by acousto-optic or galvonometer mirror control. Acousto-optic devices are limited by the time-bandwidth product to approximately 2000-element capability. Galvonometers are capable of producing up to 10,000 elements per scan at approximately 100 scans per second. However, the design must allow the mirror to over scan the desired field to reduce inaccuracies due to scan non-linearity. To achieve 9,200-element or 46,000-element resolution with low-inertia type laser deflectors requires a similar adjacent scan approach, with its associated critical edge matching.

Of the electron beam types, the most useful are the high-resolution flying spot CRT and the image disectors which are capable of achieving 3,000 to 4,000 elements per scan. Adaptation of these well-recognized technique to 9,200-element resolution requires, however, 3 adjacent sub-rasters and at least 12 to achieve 100 ℓp/mm performance. Conversely, utilizing a single flying spot CRT for "window" applications at, say, 4,000 elements per scan will cover a format width of 20 mm at 100 ℓp/mm in the image plane; this window is 8.7 percent of the full format.

Thus, the flexibly-scanned electron beam and laser beam systems do not offer a practical solution to both the window and full format scanning requirements because of the difficulty of assembling the full frame to requisite accuracy and uniformity from an array of adjacent sub-rasters.

Solid-state devices,on the other hand, can be butted by methods previously described, and, because of their small size, can rather easily be grouped to effectively produce one continuous line array of very large numbers of pixels. Hence, high resolution scanning of large formats is possible. To cover a 230-mm format at 100 ℓp/mm would require roughly 27 arrays (1728 elements each) mounted on a ceramic substrate. Each array is totally independent of all others on the substrate, thus allowing selectable swaths (windows) to be scanned merely by electronic addressing techniques. Pixel sizes of 13 by 13 μm are commercially available implying only a 2.6 x optical reduction to achieve 100 ℓp/mm. It is also noted that the

solid-state industry is predicting the commercial availability of linear arrays containing up to 12,000 elements each by 1980. These predictions are based on current development activities and trends.

Two alternatives to the solid-state approach involve adaptations of high-quality recurrent laser scanners. The first method employs rotating mirrors as deflectors and requires an angular deflection θ to satisfy resolution, N_θ, with a scanning aperture width, D, in accordance with the laser scan equation,

$$N_\theta = \frac{\theta D}{a\lambda} \text{ elements per scan,}$$

in which λ is the operating wavelength and a is an aperture shape factor, $1 \leq a < 1.5$.

The second method employs a drum-type configuration, in which the entire 230 x 230 mm format may be scanned or recorded at variable spot size, line spacing and drum speed. It entails a translation of an objective lens with respect to the storage medium to attain a resolution N_s in accordance with the relation

$$N_s = S/\delta \text{ elements per scan,}$$

in which S is the scan distance and $\delta = aF\lambda$ is the scanning spot size and F is the effective f-number, f/D; f is the focal length of the lens of aperture width D, and a and λ are as defined above.

Although the drum method is fundamentally simple, compared to the rotating mirrors, and can attain extremely high resolution with high uniformity it, like the other method, suffers from a poor duty cycle in the window mode. In both cases, a full-format width scan must be executed in a series fashion rather than parallel, while electronic aperturing selects the data portion that synthesizes the window. In contrast, there is essentially no dead time associated with the window mode when using solid-state linear arrays, because all pixels in the line are imaged onto the array simultaneously. Since individual segments of a fabricated array can be switched on and off selectively, only the pixels comprising the window need be read out, and this is

accomplished during the integration period associated with the next line being imaged onto the array.

If applications and operating scenarios planned for the digital output of the scanner "never" have need for large segments of the frame at the maximum resolution inherent in the input, another approach can be considered. A practical solution to the window-full format requirements might be to adapt a high-quality recurrent laser scan system of such design that approximately 10,000 or so elements of resolution may be conveyed over an adjustable format from 230 to 46 mm, to view the window at high resolution (100 ℓp/mm) and the entire image at 20 ℓp/mm. An appropriate single instrument for accomplishing this task is one that transfers the same 10,000-element raster to a variable image area, under the control of the data analyst. In principle, this entails the establishment of a high-quality, 10,000-element-by-10,000-line raster, and imaging that field of view upon a variable format or window size, variable over a 5:1 range.

One method of accomplishing this variable size is to start with a 10,000-element line scan and transfer it through selectable objective lenses (of different focal lengths) to the image surface to form the desired line scan lengths over the region of interest. The image surface is, in turn, translated in the across-scan direction to form the image raster, being translated at such speed as to form the required line spacing for the raster size selected. This procedure automatically adjusts spot size while maintaining constancy of the total number of elements over the field of view.

It is not likely, however, that this compromise with regard to resolution would be acceptable from an operational point of view, because there are many mapping related functions that require as much information as is available in the image, and sometimes more, to be accomplished satisfactorily.

Regarding format accommodation and resolution, the following conclusions can be drawn:

- The state-of-the-art in all the candidate technologies, except perhaps solid-state area arrays, will support the requirements of a window scanning mode.
- Only rotating drum, translating flat bed, and rotating mirror systems can satisfy the full format resolution requirements with a single unit.
- Optical and electronic butting techniques that allow the fabrication of solid-state detector assemblies with a sufficient number of elements per scan line to satisfy full format requirements at high resolution have been demonstrated. These assemblies are small compared with other technologies and permit extremely high data rates.
- Rotating drum, translating flat bed, rotating mirror and solid-state linear array assemblies can be adapted to both window and full format operating modes. However:
  - Flat-bed systems are extremely slow.
  - Rotating drums and rotating mirrors are inefficient in the window mode because of the duty cycle; i.e., complete lines of data must be scanned with the windowing accomplished by subsequent signal processing.

Format accommodation and resolution capabilities of the various technologies considered, related to the requirements set forth in Table 4-1, are summarized in Table 4-2.

4.3 SPOT SIZE VARIATION

The following three techniques for varying spot size are particularly applicable to drum scanners, although they may also be applied to the rotating mirror scanners for adjusting spot size. The three techniques are:

a. Variable objective lens

b. Variable objective lens aperture

c. Variable objective lens focus

In all cases, the scan periodicity must be altered to accommodate the varied spot size, retaining the fixed relationship of line count with respect to spot size, i.e., the larger the spot, the lower the line count. The variable objective lens method (as in a microscope turret) provides relatively uniform optical efficiency, simply by converging the same input light flux across aperture D over a variable focal length; hence a variable F-number and resulting diffraction-limited spot size, $\delta = aF\lambda$. It is possible to design the lens switching system to avoid critical refocusing for any but the highest resolution mode, by accessing the lenses such that they account for the differences in focal lengths by establishing a fixed image plane. The tolerance on depth of focus increases rapidly (by the square of the F-number) as the F-number is increased to increase the spot size.

The variable aperture method is the simplest to implement, for it requires no change in objective lens nor in its focal position. It entails the insertion of a variable iris-type aperture, such as employed in camera F-number adjustment. The trade-off is the loss in laser light as it is apertured more completely to yield the highest F-number (largest spot, lowest resolution). Unfortunately, this is contrary to the normal requirement of laser power as a function of resolution in a constant-bandwidth system. The lower resolution case, having the larger spot, requires traversal of correspondingly more image area per unit time. The insertion of an aperture to enlarge the spot by diffraction further increases the demand for laser power to overcome this loss.

The variation of lens focus maintains some of the better factors of both above methods; it requires only a single lens and it retains full laser power. However, each focal position need be carefully adjusted to provide the specific defocus corresponding to a desired spot size. This can be instrumented with a predetermined positional arrangement to establish requisite spot size on command.

The following two methods can be used to vary the effective spot size with solid-state scanning systems:

a. Electronic or digital pixel combination logic

b. Optical magnification.

The electronic approach was discussed in Section 3 and illustrated in Figure 3-16. To achieve the 5 to 1 range desired the following signal buffering capacity will be required: one line with N/2 pixel capacity for 2X spot enlargement; two lines with N/3 pixel capacity for 3X; three lines with N/4 pixel capacity for 4X; and four lines with N/5 pixel capacity for 5X enlargement. N equals the maximum number of pixels in a scan line.

Optical magnification can be applied in two different ways. In one, enough detectors are provided to satisfy the highest resolution requirement and the entire line is then magnified optically to decrease resolution (enlarge effective spot size). Since the full magnified line will exceed the maximum input format, it would be advantageous to employ windowing logic that is keyed to the selected magnification and that deactivates an appropriate number of individual arrays in order to reduce the volume of data to be processed.

The second approach employs a separate 2000-element array for the window scanning mode. It would be translatable in the film width direction for positioning purposes along that axes, and would be magnified or reduced optically to achieve the desired resolution. In this approach, the pixel combination logic previously mentioned would be used to adjust resolution for the full format mode.

4.4 GEOMETRIC LINEARITY

Regarding geometric linearity, it is well appreciated that all electronic and laser techniques require extreme control to achieve high geometric uniformity. Some systems, however, are more prone to non-uniformities. Those that are sensitive to non-uniformity are the flexible (random-access) scan systems, both electron-beam and laser beam systems that are non-mechan-

ically scanned. They require feedback of varying degrees of severity to achieve spatial non-linearities under the 0.1 percent range (1 part in 1000). Various index beam and grating read-out techniques have been used to rectify the error during scan, and linearity on the order of 0.01 percent has been achieved. The grating reference technique is most adaptable to the laser beam scanned systems. Ignoring solid-state arrays for the moment, the systems fundamentally most uniform are the high inertial rotating scan, drum scan, and flat bed scanning methods that have precise mechanical indexing of the scan angle or position, and are <u>not</u> followed by subsequent wide angle ("flat-fielding") optics. These are capable of providing geometric linearities of one part in tens of thousands of resolution elements. Geometric linearity of 1 to 2 parts in 100,000 has been achieved in drum-type laser scanners and flat bed scanners, but it does require great care in design and implementation and usually limits the scan rate significantly. Geometric linearities of flexibly-scanned systems (electron and laser) of this quality are presently beyond the realm of realizability.

In solid-state arrays, the geometric accuracy of the placement of each pixel in individual arrays approaches ±0.1 micrometer. The arrays can be butted to an accuracy of 1 to 2 micrometers. However, once fabricated, the geometry remains constant with time (assuming proper temperature control). Therefore, post-fabrication calibration can reduce overall error if required. Hence, along one axis, accuracies on the order of 1 part in 250,000 or .0004 percent can be achieved. If required, this can be improved on by calibration and compensation. Furthermore, since solid-state arrays do not employ a scanning beam, there is no electronic distortion inherent in the detector.

Assuming the use of a precision translating stage such as employed in currently available microdensitomers, accuracies on the order of 5 micrometers over 250 mm, or 0.002 percent, can be achieved in the other direction with existing designs.

The geometric linearity characteristics of the technologies considered are summarized in Table 4-3.

4.5 PHOTOMETRIC ACCURACY AND DYNAMIC RANGE

The anticipated dynamic range of typical input material being 0.2 to 2.5 density units (63.1 to 0.316 percent transmission or reflection) represents a ΔD of 2.3 and a transmission ratio of some 200:1. To accommodate this dynamic range the signal may be digitized to 8 bits (256 levels), requiring system signal-to-noise ratio in the vicinity of 24 db (250:1 in intensity). This is an extremely demanding requirement if taken at the pixel level, for it implies that two adjacent elements are capable of being measured to 250 units and 1 unit of intensity, respectively. The modulation corresponding to that measurement is $(250-1)/(250+1) = 0.992$; that is, 99 percent MTF at the pixel level. This corresponds to the limiting spatial frequency of interest (say, 100 ℓp/mm). However, since maximum density differences of an original scene normally occur over macroscopic rather than microscopic spatial intervals, the ΔD of 2.3 (200:1) is likely to occur only at much lower spatial frequencies; probably lower than 1/10 of the limiting spatial frequency. Therefore, from the photometric point of view, a system should have a high MTF at approximately 1/10 of the limiting spatial frequency. This establishes a more realizable MTF and signal-to-noise requirement, compatible with a system whose MTF at the highest spatial frequency of interest is 50 percent. It is well to emphasize that a 50 percent MTF is a very substantial performance at the pixel level, as compared to the more familiar limiting performance of test bar measurements where the MTF approaches zero, that is, barely perceptible contrast.

This system MTF of 50 percent over more than 10,000 pixels per line is available only from the highest quality laser systems, microdensitometers, and solid-state devices discussed above.

The laser system is unique in its ability to provide extremely high signal-to-noise ratio. This is because the laser itself is a relatively noise-free source (50 to 60 db with low frequency noise suppression) which can

provide adequate power to override systematic noise of detectors, preamplifiers and imaging-materials. Photometric accuracies on the order of 0.01 density unit have been achieved with laser systems.

Electronic image sensors and CRTs of the highest quality and uniformity are not known to be capable of density discrimination to better than ± 0.02D or 5 percent intensity change over 100:1 total intensity range ($\Delta D = 2$). The 5 percent intensity variation is representative of the residual shading characteristics of electronic image sensors and CRT's, even after utilization of shading correction circuitry, such as that in the Hamamatsu C1000 series of high-performance vidicons.

The difficulty with both electronic and laser-addressed scanners which execute an angular change in beam position is that the electron-optical or geometrical-optical performance is extremely difficult to maintain constant over the full angular subtense or field angle of the lens system -- either electronic or optical. In addition to the beam landing errors, the sensing or phosphor coatings must be deposited with extreme uniformity so that even ideal electron beam landings create an effect which is constant over the entire surface. In laser beam systems deflected to the resolution limit with acousto-optic devices, there is an intensity fall-off in output at the margins of scan as the beam departs from the Bragg angle as it traverses the device. In all cases, compensations are possible, but are extremely complex to accomplish non-uniformities within ± 1 percent.

One exception to this angular scan situation is the laser system which is deflected through an angle with a single mirror, and is used directly on a curved surface -- not flat-fielded. In this case, the beam landing can be made uniform without limit, determined mainly by the uniformity of the stationary beam illuminating the deflector. This ultimate in uniformity can also be achieved, in principle, with the rotating drum and flat bed scanners because no angular change is executed. The beam is translated with respect to the storage medium instead.

The dynamic range of solid-state detectors can span four orders of magnitude. SSPD's are typically in the 10,000:1 category, whereas CCD's are in the 2500:1 category, more than enough to cover the anticipated 200:1 scene brightness ratio of typical imagery to be scanned (density difference of 2.5 - 0.2 = 2.3). Furthermore, their output is linearly proportional to the input flux over most of this range and their noise characteristics are very favorable.

Since the accuracy of the encoding process depends upon the system random noise and the resolution of the encoder (number of levels), the probability that a signal will be correctly quantized can be determined by examining the ratio (δ) of the RMS noise at the output of the detector (σ_D) to the size of each A/D conversion level (ΔN):

$$\delta = \frac{\sigma_D}{\Delta N}$$

Intuitively we see that the larger the value of δ, the smaller the probability that the signal will be correctly encoded (to within $\pm 1/2\ \Delta N$). Table 4-4 lists the quantization error probability as a function of δ. It was generated using Monte Carlo techniques, as discussed in reference 1. The values listed represent the probability of a correct quantization, zero error, and the probability of quantization errors of $\pm$ 1 level, $\pm$ 2 levels, and so on. The table indicates that for δ less than 0.40, the encoder value will be accurate to within $\pm$ 1 level. To maintain this degree of fidelity during the scanning process it will be assumed that δ max for the scanner should not exceed 0.40. Hence, given an A/D encoder of 8 bits (256 levels), the one-sigma noise level of the scanner (σ_D) should not exceed 40 percent of the energy value assigned to each level.

The noise levels of CCD devices, as an example, are typically 100 to 200 electrons per pixel, or about 1 $\mu j/M^2$ of equivalent exposure. If the light source intensity is adjusted to provide a 10:1 signal/noise ratio at maximum scene density (D = 2.5), then the maximum signal for a 200:1 dynamic range would be 1 $\mu j/M^2$ x 10 x 200 = 2000 $\mu j/M^2$. For an 8-bit encoder,

TABLE 4-4

QUANTIZATION ERROR PROBABILITIES

δ	QUANTIZATION ERROR						
	0	±1	±2	±3	±4	±5	±6
.05	.956	.044					
.10	.927	.073					
.15	.885	.115					
.20	.843	157					
.25	.803	.197					
.30	.757	.143					
.35	.727	.272					
.40	.681	.317	.002				
.45	.641	.355	.004				
.50	.609	.381	.010				
.55	.579	.407	.014				
.60	.544	.435	.021				
.65	517	.447	.036				
.70	.487	471	.042				
.75	.468	.470	.058	.004			
.80	.452	.466	.077	.005			
.85	.422	.483	.090	.005			
.90	.397	.488	.108	.007			
.95	.379	.494	.115	.012			
1.00	.371	.475	.139	.016	.001		
2.00	.195	.348	.235	.138	.059	.021	.004

each level should therefore be 2000/256 = 7.8 $\mu j/M^2$ of exposure. Thus for CCD arrays $\delta_{10} = \sigma_{10}/\Delta N = 1/7.8 = 0.13$, which is much lower than the maximum value of δ that will limit quantization error to ± 1 level (δ max = 0.4). Table 4-4 implies a 90 percent probability of correct quantization and zero probability of an error in excess of ± 1 A/D level. Thus, it is conceivable that encoding in excess of 8 bits, possibly to 9 bits, is feasible. This would decrease the approximation error by two times while still resulting in a maximum error of ± 1 level. However, the non-uniformity in photo-response* that is typical between elements of a CCD array was not considered in the above analysis. It has been found to be approximately ± 6 percent in extensive testing and array characterization programs at Perkin-Elmer. Since it remains fixed as long as operating temperatures are controlled, once calibrated, it can be compensated for.

4.6 DATA RATES

Only laser scanners and solid-state linear array scanners can provide more than 10,000 pixels per line at rates exceeding 0.75 million pixels per second (refer to Tables 4-2 and 4-3). Laser scanners employing rotating mirrors for deflection along one axis and that produce 55,000 pixels per line at a rate of 100 million pixels per second have been developed. Oscillating mirror scanners can provide about 10,000 pixels per line at a maximum rate of 1 million pixels per second, however, they are not capable of the 46,000 pixels per line required for 100 ℓp/mm resolution over the full format.

The data rates achievable with rotating drum systems is limited primarily by the rate at which drums can be rotated while maintaining accurate speed control, dimensional stability, and the film in focus on the focal surface. Rates up to 1.5×10^5 pixels per second are reported in the literature.

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*Photo-Response Non-Uniformity is herein defined as the difference in response levels between the most sensitive and least sensitive pixel, expressed as a percent of saturation level.

Flat bed instruments, in various configurations can scan at speeds from 50 to 200 mm/sec and reportedly maintain geometric accuracies on the order of ± 5 micrometers over several centimeters of travel. The 200-mm rate with a 5-micrometer spot would yield a 4×10^4 pixel per second rate.

Solid-state arrays (Fairchild CCD 131, for example) can be driven at a data rate of 20×10^6 pixels/sec. However, several arrays must be operated in parallel to scan 46,000 pixels in a 230-mm line. Typical scan velocities for this 230-mm swath could be from 125 to 250 mm per second, assuming integration intervals of 10^{-4} second per sample (line of pixels) and average flux levels of 250 $\mu j/M^2$. However, if it is assumed that the precision translating stage is limited to 100 mm/sec, the resulting rate would be 20,000 scan lines per second or 9.2×10^8 pixels/sec at the highest resolution.

Data rate capabilities of the different technologies considered are also summarized in Table 4-3.

SECTION 5

CONCLUSIONS

The critical requirements imposed on an image scanner for digital mapping applications are resolution (in total number of elements per viewing area), uniformity of performance over that area, and speed.

Both resolution and uniformity appear to be beyond the capability of flexibly scanned systems, electron beam or laser beam-addressed.

Even the highest performance electron-beam systems are not capable of covering the full format with requisite number of resolution elements at sufficiently high contrast and detectability to allow adequate dynamic range and scan linearity. The montaging of strips or areas of sub-rasters to allow the use of such systems is extremely unattractive because of the critical edge-matching requirements to achieve continuity with accuracy.

Mapping applications also require different operating modes, i.e., scanning a full format (230 x 230 mm area) and a smaller "window" image at high resolution. Systems adaptable to all these requirements include drum-type laser scanners, rotating-mirror laser scanners, and solid-state scanners comprised of a series of optically butted linear arrays. In all cases, careful design and implementation is essential.

The rotating drum and mirror approaches are inefficient in the window mode because of their duty cycle, whereas the solid-state approach is equally efficient in both the full format and window mode.

If different scanners are planned for each mode, then oscillating mirror technology can be adapted to satisfy a "window only mode" in conjunction with precision positioning stages. Some of the electronic scanners can

also be adapted to the "window only mode" if geometric and photometric accuracy requirements are relaxed.

It should also be noted that most of the scanning technologies discussed in this report have a relatively long history (15-30 years). The embodiments of scanner systems using these technologies have thus benefitted from significant developments over these relatively long periods and can be taken to represent near maximum or optimum refinement. One technology, however, is relatively new and has not benefitted from many years of refinement. This technology, solid-state imaging arrays, will very likely see significant improvement in the coming years. Certainly, the relative infancy of this solid-state array technology and the rapid rate at which refinements in terms of number of elements per array, element size and spacing, and noise characteristics are being introduced strongly suggests that their capabilities and associated implementation simplicity will far surpass other alternatives for most scanning applications in the very near future.

The operating environment intended for the scanner, i.e., production or research and development, also significantly influences the requirements imposed on it. Consequently, it is concluded that the application scenario and intended environment must be known and resulting requirements carefully evaluated and ranked before the most appropriate technology can be selected and a system design recommended.

SECTION 6

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APPENDIX A

THE DETECTOR PHASING FUNCTION

If we consider an input square or sine wave and a detector array, there are two distinctly different situations as illustrated at A and B of Figure A-1a. Here are shown two spatial frequencies, k = 1/H and k = 1/2H. At A the input is in phase with the array; at B it is out-of-phase.

Examination shows that, at A the signal* is a maximum for k = 1/2H and vanishes for k = 1/H. At B the array has been shifted 1/2 pixel in the frequency direction, and here the signal is zero at both frequencies. Hence, it is clear that the array response will not only be a function of the spatial frequency itself, but also of the phasing of a particular image frequency with respect to the array. In general, the phasing distribution will be random.

Figure A-1b illustrates a derivation of the phasing function.

Consider a spatial frequency $k = \frac{1}{\lambda}$, where

$$y = A_o + A_i \sin \frac{2\pi x}{\lambda} = A_o + A_i \sin 2\pi kx \qquad \text{(A-1)}$$

and an array of detector elements, e_n, of width ω with the center of one of the elements located at a distance x_o from the maximum of y.

If the location of x_o is random over the range $-\frac{\omega}{2} \le x_o \le \frac{\omega}{2}$, then the total signal over the pixel of width ω will be

$$A = \frac{A_i}{\omega} \int_{x_o - \frac{\omega}{2}}^{x_o + \frac{\omega}{2}} (\sin 2\pi kx)dx \qquad \text{(A-2)}$$

Therefore

$$\frac{A}{A_i} = \frac{\sin \pi k\omega}{\pi k\omega} \cos 2\pi kx_o \qquad \text{(A-3)}$$

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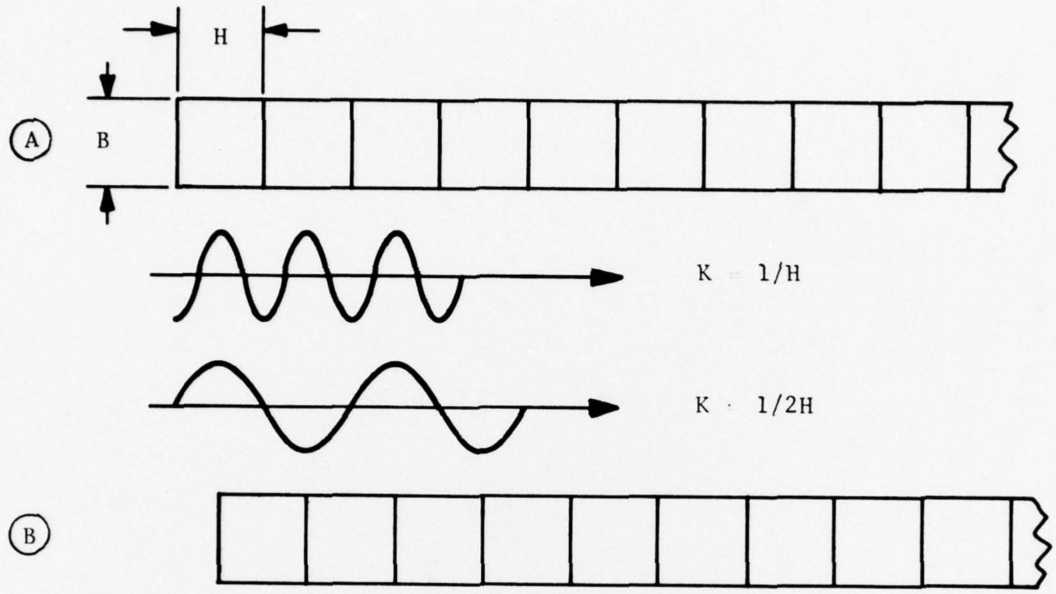
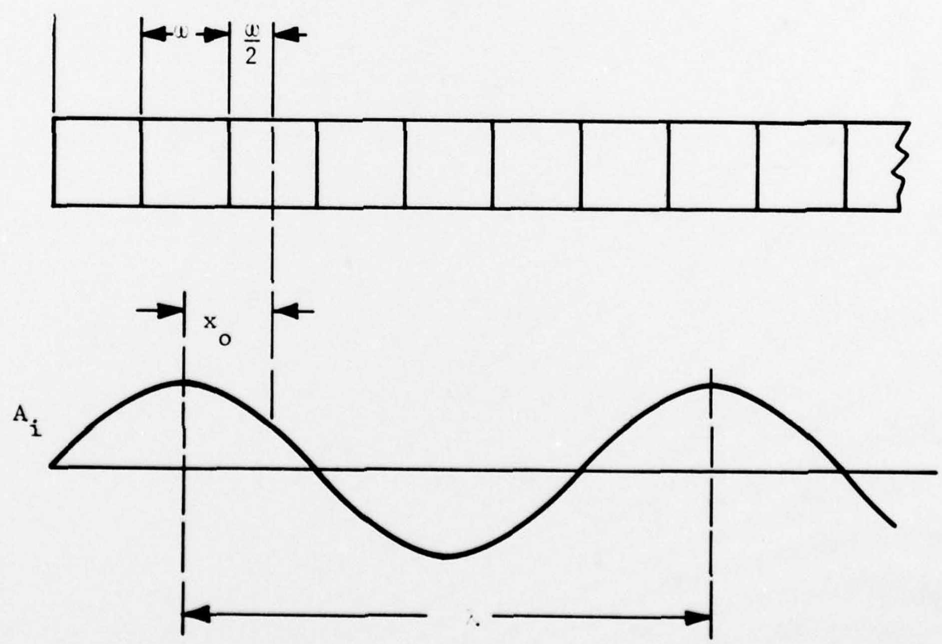
*Signal is defined as the difference of the input for two adjacent detectors.



(a) Concept



(b) Derivation of Detector Phasing Function

Figure A-1. Detector Phasing Function

This represents the signal amplitude reduction factor, or detector MTF resulting from detector location x_o.

The maximum value for $x_o = 0$ is

$$MTF_{max} = \left(\frac{A}{A_i}\right)_{max} = \frac{\sin \pi k\omega}{\pi k\omega} \tag{A-4}$$

and the minimum value for $x_o = \pm \frac{\omega}{2}$, is

$$MTF_{min} = \left(\frac{A}{A_i}\right)_{min} = \frac{\sin \pi k\omega}{\pi k\omega} \cos \pi k\omega \tag{A-5}$$

At the limiting spatial frequency $k = \frac{1}{2\omega}$, these become

$$MTF_{max} = \frac{2}{\pi} \tag{A-6}$$

and

$$MTF_{min} = 0 \tag{A-7}$$

The average MTF, for random x_o is given by

$$MTF_{av} = \left(\frac{A}{A_i}\right)_{av} = \frac{2}{\omega} \int_o^{\frac{\omega}{2}} \frac{\sin \pi k\omega}{\pi k\omega} \cos 2\pi kx_o (dx_o) \tag{A-8}$$

$$= \left[\frac{\sin \pi k\omega}{\pi k\omega}\right]^2 = M_d$$

Directional considerations also enter into the problem in the case of detector arrays, since the detectors are, in general, rectangular rather than square. For linear arrays, the problem is even more complex, since the system may be operated in a number of ways with respect to the direction transverse to the array.

If the image is scanned in such a way that the linear array is advanced exactly one width, B, between scans, in an intermittent fashion, then the models described here are valid in both directions, when the appropriate pixel dimension in the direction of concern is specified.

However, in a line array system, it is the designer's option to alter the scan transverse to the array at will, to provide any amount of overlap between scans that may be appropriate. This adds another factor to the analysis which is not discussed here.